ELECTRICAL TRANSMISSION AND DISTRIBUTION

VOLUME IV

SWITCHGEAR: PART II

VOLUME IV

CARE AND OPERATION OF SWITCHGEAR

BY

V. A. BROWN, B.Sc. (Tech.), A.M.I.E.E.

IRONCLAD SWITCHGEAR

BY

JOHN M. GOODALL

PROTECTIVE SYSTEMS FOR A.C. MAINS

BY

BRUCE HAMER LEESON, A.M.I.E.E.

ELECTRICAL TRANSMISSION AND DISTRIBUTION

A COMPLETE WORK BY PRACTICAL SPECIALISTS DESCRIBING MODERN PRACTICE IN THE TRANSMISSION AND DISTRIBUTION OF ELECTRICITY SUPPLY

EDITED BY

R. O. KAPP, B.Sc.

CHARTERED ELECTRICAL ENGINEER

VOLUME IV

SWITCHGEAR: PART II

LONDON

SIR ISAAC PITMAN & SONS, LTD.

PARKER STREET, KINGSWAY, W.C.2

BATH, MELBOURNE, TORONTO, NEW YORK

1929

PRINTED IN GREAT BRITAIN
AT THE PITMAN PRESS, BATH

ELECTRICAL TRANSMISSION AND DISTRIBUTION

CONTENTS

VOLUME I

Overhead Transmission Lines. (*Now ready.*)

VOLUME II

Power Cables. (*Now ready.*)

VOLUME III

Switchgear, Part I. (*Now ready.*)

VOLUME IV

Switchgear, Part II. (*Now ready.*)

VOLUME V

Sub-station Work, Part I. (*Now ready.*)

VOLUME VI

Sub-station Work, Part II. (*Now ready.*)

VOLUME VII

Instruments and Meters. (*Ready end of March.*)

VOLUME VIII

Auxiliary Plant. (*Ready end of April.*)

Each 6s. net

PRINTED IN GREAT BRITAIN
AT THE PITMAN PRESS, BATH

PREFACE

The first section in this volume, dealing with Care and Operation of Switchgear, is of particular importance, as upon the reliable working of Switchgear depend the continuity of supply and the safety of human life. Commencing with descriptions of modern types of isolating switches, circuit breakers and motor operating gear, the author goes on to describe the operation of Busbar selection devices, safety shutters and doors, earthing and interlocking devices, the care of insulation and of overload and protective gear. This section will be extremely valuable to all concerned in the operation of Switchgear, as the author writes from the point of view of those engaged in the practical handling of power.

The second section deals with Ironclad Gear, which has been specially developed for use in Industrial and Mining work. Examples of modern practice are given of wall-mounted gear, drawout gear, flameproof gear, vertical plugging switchgear, while notes are also given on thermal circuit breakers and leakage current trips.

The volume concludes with a section on Protective Systems for A.C. Mains. One of the most important responsibilities of power station engineers is the maintenance of a continuous supply under all conditions of service, and the necessity of providing efficient Protective Systems to secure this continuity of supply cannot be too strongly emphasized. The most desirable quality of a protective system is that it shall always isolate a faulty main without involving interruption to a healthy one in its neighbourhood.

The author gives prominence to a method of rating employed by him for some years, based on the use of stability diagrams which enable stability to be expressed as a definite rating additional to the commonly used fault-setting rating. Although the title of the section would include every Protective System applicable to A.C. mains, those relating to low and medium voltage systems, such as 440 volt, have been excluded.

CONTENTS OF VOL. IV

SECTION XIII

CARE AND OPERATION OF SWITCHGEAR

BY

V. A. BROWN, B.Sc. (Tech.), A.M.I.E.E.

SECTION XIII

CARE AND OPERATION OF SWITCHGEAR

SWITCHGEAR should possess the following qualities, which are of paramount importance—

1. Reliability and safety under normal switching, voltage and current carrying conditions.
2. Ability to withstand the shocks of carrying and interrupting short-circuit current without danger to adjacent apparatus, buildings or persons.
3. Ability to disconnect, automatically, any faulty apparatus or sections of the network with rapidity and unerring discrimination.

The preservation of the above qualities depends in no small measure on proper care and operation, and this section of the work is intended as a guide to the principles involved.

SWITCHING OPERATIONS

The operating principle of switches, circuit breakers, isolating and busbar selecting devices consists of the insertion and withdrawal of a movable link in the copper circuit, thus leaving one or more gaps per phase insulated by air or oil. The movable link is actuated by a mechanism, the prime mover of which is a rotating shaft or a reciprocating link. Control of the breaker is obtained by coupling the shaft or link to a manual or electrical operating gear.

Switches and Circuit Breakers. Switches and circuit breakers are of similar construction, the difference being that a switch is not intended for automatic operation under short circuit conditions. The internal

portions of an 11,000 volt oil circuit breaker are shown in Fig. 1. The wedge-shaped moving contacts are raised and lowered by a rotating shaft, at each end of which a lever is attached. Each lever operates a side lifting bracket which slides on a vertical guide rod

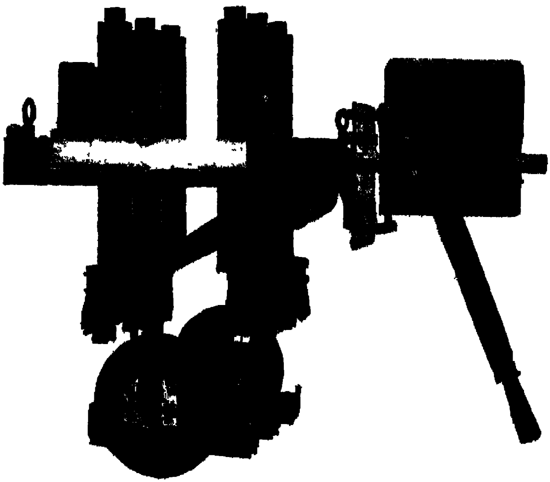


FIG. 1. MANUALLY-OPERATED OIL CIRCUIT BREAKER

fixed to the breaker top plate. The breaker mechanism is buffered at the end of the opening stroke by an oil dashpot located at the lower end of each guide rod. Buffering at the end of the closing stroke is accomplished by the two accelerating springs, which also serve to accelerate the moving contacts during the opening stroke.

For manual operation, a hand operating gear is coupled either directly to the operating shaft at the

breaker location as in Fig. 1, or indirectly through a train of operating rods and bell crank levers as illustrated in Fig. 2. Remote mechanical operation is only

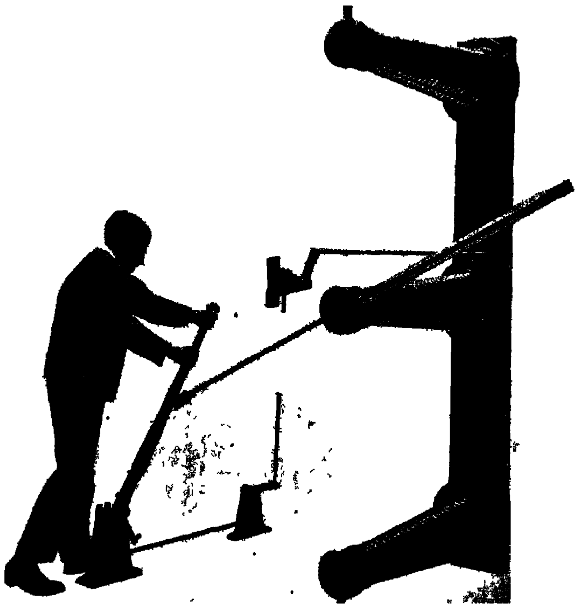


FIG. 2. REMOTE MECHANICALLY-OPERATED ISOLATING SWITCH

satisfactory for comparatively short and straight drives. Remote control is better obtained by electrical operation. The electrical operating gear, either solenoid or motor, is connected directly to the breaker as in Figs. 3 and 4. The control panel can be located in any convenient position remote from the circuit breaker.

Manual and electrical operating mechanisms usually consist of an arrangement of cranks and toggle levers, which can be held in the closed position by some form

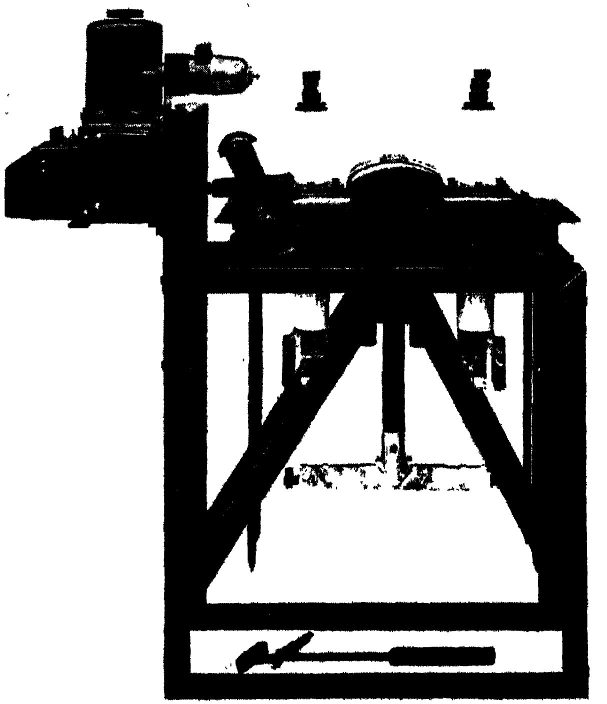


FIG. 3. OIL CIRCUIT BREAKER, ELECTRICALLY OPERATED BY SOLENOID

of catch. The latter is released by the plunger or armature of a tripcoil. The plunger or armature can also be operated by hand. Tripcoils are of two general types, namely, attracted armature and solenoid (or

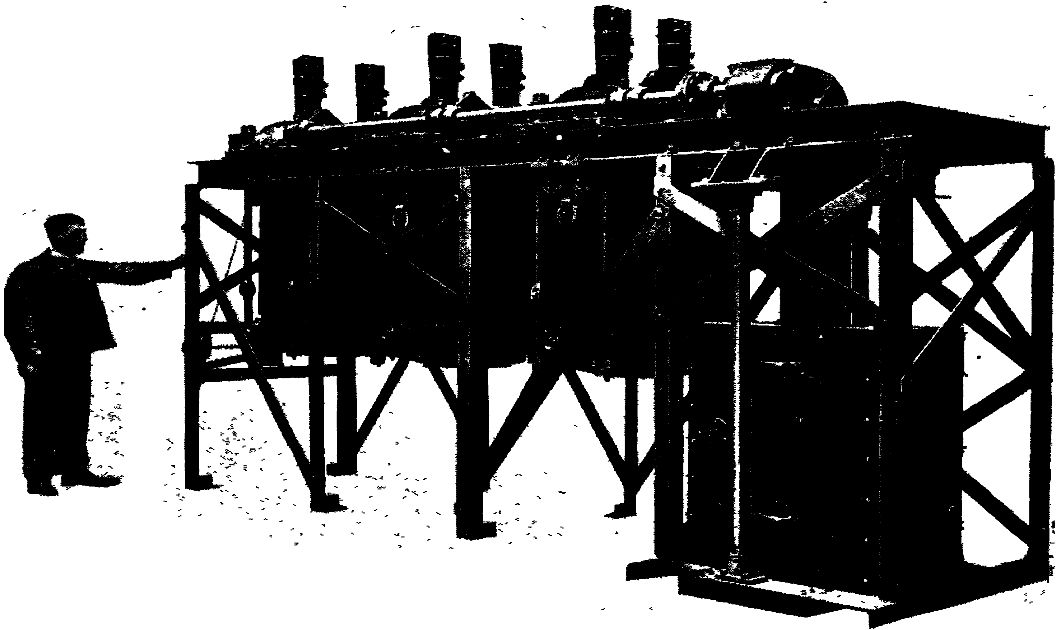


Fig. 4. Oil Circuit Breaker, Motor Operated

plunger) type. The closing movement usually has a "trip-free" characteristic, i.e. the breaker is free to trip at any point of the movement. This feature is

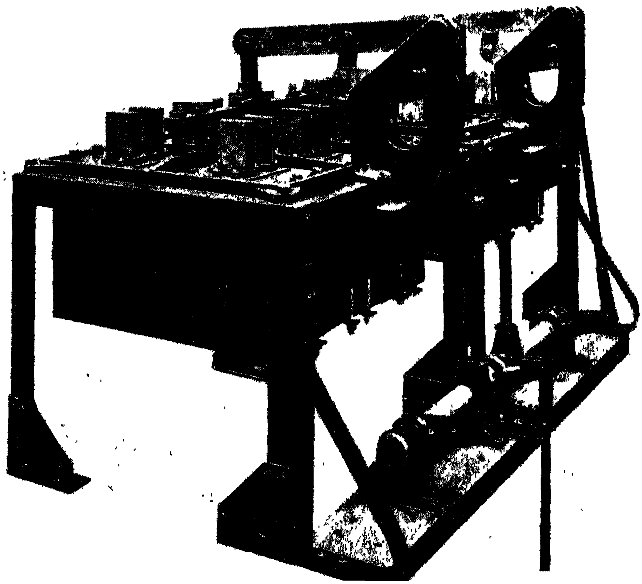


FIG. 5. REMOTE, MECHANICALLY-OPERATED, HEAVY CURRENT, OIL CIRCUIT BREAKER

generally obtained mechanically in the operating mechanism, but one large American company uses solidly-coupled operating gears and the trip-free characteristic is obtained by electrical relays. A toggle lever is clearly shown in Fig. 5, which is another example of remote mechanical operation.

A hand-operating gear is illustrated in Figs. 6 and 7, the former showing the ball catch free from the grooved

operating rod and the latter showing the operating gear in the closed position, i.e. with the hard steel ball *F* in groove *E* and the roller *G* in position over the ball. The tripcoils, of which the balance weights *J* and calibration arms *H* are shown, release a spring-loaded hammer located at the far side of the trip box. The

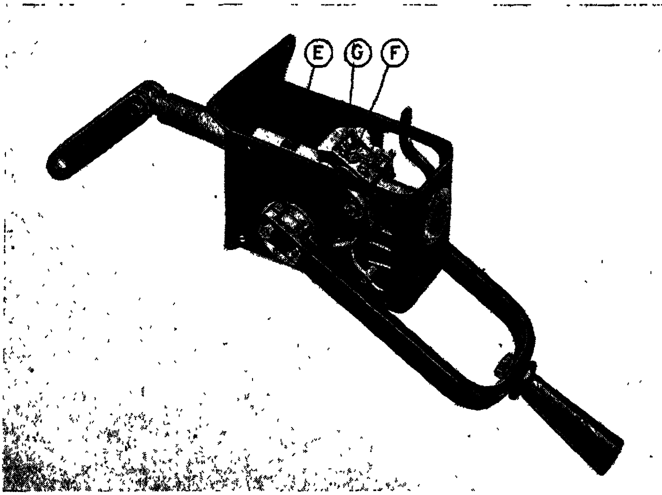


FIG. 6. HAND OPERATING GEAR
(Open)

dropping of the hammer displaces the roller and allows the ball to rise out of the groove under the pressure exerted on the operating rod by the accelerating springs of the circuit breaker. Thus, the breaker opens and the operating rod assumes the position shown in Fig. 6. The tripping hammer is reset by the upward movement of the hand lever during the process of re-engaging the ball with the groove, prior to reclosing the circuit breaker. The use of a spring-loaded mechanical relay allows the trip coils, which are of the attracted

armature type, to be made sensitive down to one volt-ampere.

A solenoid type of operating gear for an outdoor oil

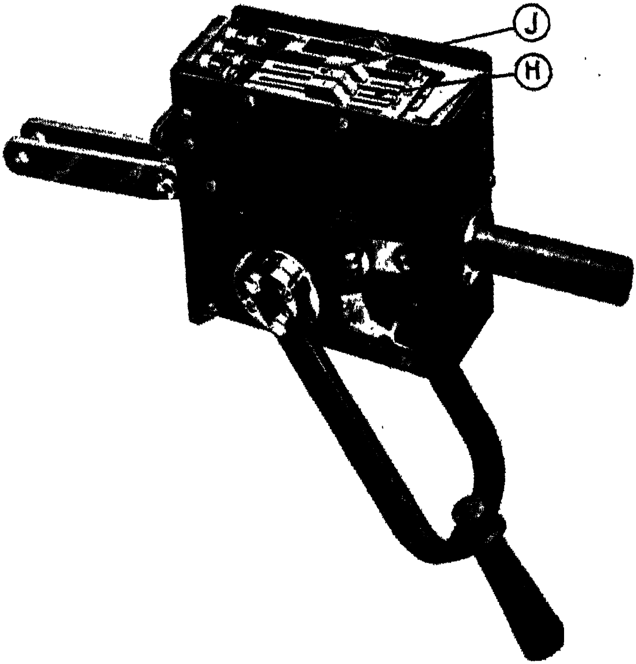


FIG. 7. HAND OPERATING GEAR
(Closed)

circuit breaker is shown in Fig. 8. The gear is housed in a weatherproof cubicle, the sides of which are not shown. The solenoid consists of a steel plunger, which is pulled upwards by solenoidal and air gap magnetic attraction. The exciting coil is ironclad and surrounds a brass guide tube in which the plunger operates. The

projecting end of the plunger is coupled, through cranks and toggle levers, to the vertical rod which operates the circuit breaker through bell crank levers located in

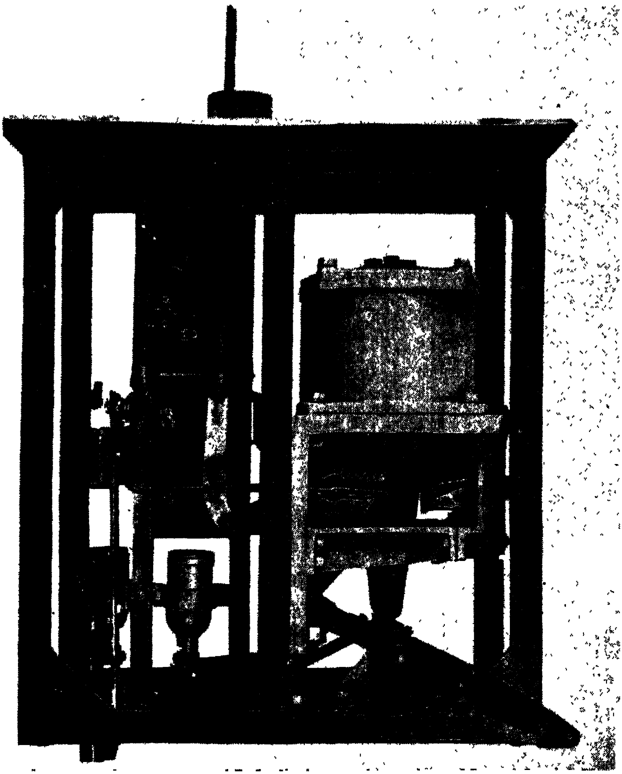


FIG. 8. SOLENOID GEAR FOR OUTDOOR OIL CIRCUIT BREAKER

the breaker top plate. The tripcoil can be seen at the right-hand side of the illustration. An emergency hand operating lever is provided at the bottom of the cubicle.

In order to reduce the size of control wiring between the switch room and control panels, each solenoid coil is energized by a contactor, which is operated by a low consumption coil. The contactor consists of an operating coil, which magnetizes a pole piece, the magnetic circuit being completed by a hinged armature, through an air gap.

The solenoid circuit is made by a pair of fixed and movable contacts, the moving contact being carried by the armature which is attracted to the pole piece when the contactor operating coil is energized. No latching device is provided in order that the armature may return to its open position when the operating coil is de-energized.

Under fault conditions, the protective relay closes a pair of contacts, which energize the tripcoil, and the circuit breaker is automatically opened. In order to clear the tripping circuit, after the circuit breaker has opened, an auxiliary switch is fitted. This switch is coupled to the mechanism which operates the circuit breaker, so that when the circuit breaker opens the auxiliary switch also opens, and vice versa. Auxiliary switches are also used for indicating and interlocking purposes, as will be described later. The closing circuits for a remote solenoid-operated oil circuit breaker are shown in Fig. 9. All main connections and busbars have been omitted in order to keep the diagram clear.

The control switch *P* is connected to the contactor operating coil *O* by multicore cable *M*. The closing of switch *P* energizes coil *O* which closes the contacts *C* of the contactor. This energizes the solenoid coil *S*, which in turn closes the oil circuit breaker. On opening switch *P*, the contactor opens its contacts and the arc is extinguished by the magnetic action of the blow-out coil *B*.

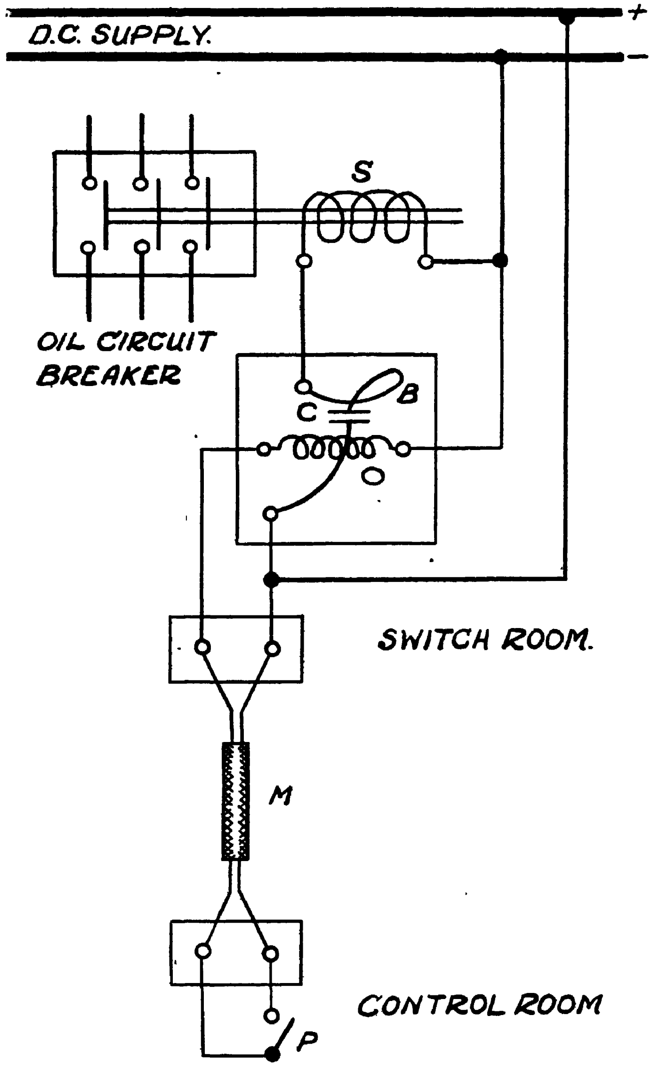


FIG. 9. REMOTE CONTROL CIRCUITS FOR SOLENOID-OPERATED OIL CIRCUIT BREAKER

Owing to the excessive kVA consumption of alternating current solenoids, their use becomes prohibitive on any but small switches and circuit breakers, and hence motor operating gear has to be used where only an alternating current supply is available. Motor operating gears are slower than the solenoid type, which latter is to be preferred when a direct current supply is available. Fig. 10 illustrates the motor operating gear used with the circuit breaker shown in Fig. 4. The motor drives a flywheel through a train of gear wheels and must be brought up to speed before the breaker can be closed. A centrifugal switch on the motor shaft, connected in series with the closing circuit, ensures that the closing operation cannot be carried out before a predetermined speed is reached. The circuit-breaker mechanism is coupled to the flywheel by a loose bolt, which can be engaged with or disengaged from the flywheel by means of a small solenoid controlled by a switch at the control panel. The kinetic energy of the flywheel is used for closing the circuit breaker. Other forms of motor operating gear use the motor for storing the closing energy in a spring or centrifugal governor. For closing small sizes of circuit breakers, the torque of the motor may be used direct through a centrifugal clutch.

It is desirable to have some form of indication of the operating position of remotely controlled switchgear at the control board. Such indication can be obtained by lamps or semaphore indicators. In some cases, a dummy diagram of the whole switching scheme is mounted above the control board as shown in Fig. 11. Indicating lamps are usually fitted on the control panels and semaphore indicators are employed in the dummy diagram. A semaphore indicator is operated by a two-way electro-magnetic device either of the attracted armature type or the solenoid type. Indication of the

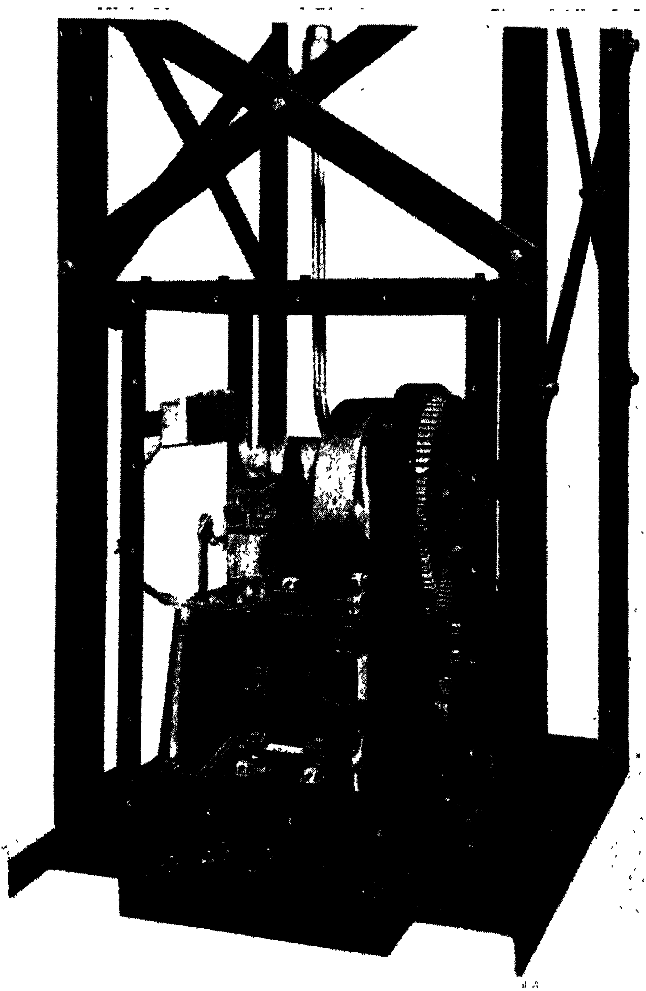


FIG. 10. MOTOR OPERATING GEAR

position of a circuit breaker, switch, isolating or selecting device, is given by a flat strip which is carried on a rotary shaft and forms part of the diagram, when in the closed position. When the semaphore is opened,

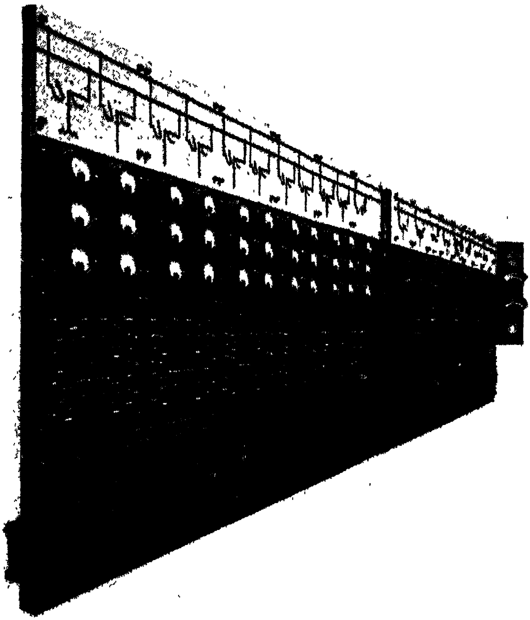


FIG. 11. DUMMY DIAGRAM AND CONTROL BOARD FOR REMOTE ELECTRICALLY-OPERATED SWITCHGEAR

the flat strip is turned through 90 degrees, thus clearly showing a break in the connections of the diagram. The operation of a semaphore indicator is controlled by a two-way auxiliary switch coupled to the operating mechanism of the switch, circuit breaker, etc., the position of which is to be indicated. A diagram of the indicating lamp and semaphore circuits for a two-way

circuit breaker or duplicate circuit breakers is given in Fig. 12. The tripping circuits, together with bell alarm, are shown in Fig. 13. The alarm bell only rings

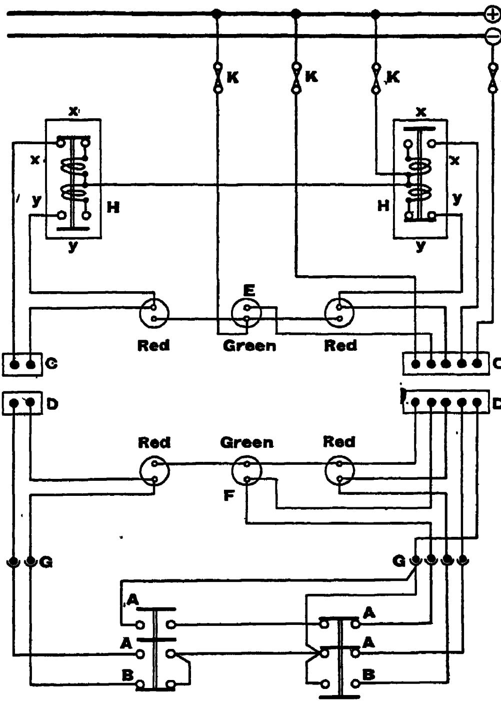


FIG. 12. INDICATING LAMP AND SEMAPHORE CIRCUITS

A—Auxiliary contacts, close when breaker opens
B—Auxiliary contacts, close when breaker closes
C—Terminal board, on control panel
D—Terminal board, unit
E—Lamps on control panel
F—Lamps on unit
G—Secondary plugging members on manually operated units only
H—Semaphores
K—Fuses
Coil *x* opens contact *x* and closes contact *y* (semaphore open)
Coil *y* opens contact *y* and closes contact *x* (Semaphore closed)

Left-hand side equipment—for front breaker
Right-hand side equipment—for rear breaker
Green lamps light only when both breakers are open
Diagram shows position of contacts when front busbar breaker is closed

when automatic tripping, by the protective relay, has occurred. A second way is provided on the tripping switch for hand tripping. The closing circuits, involving

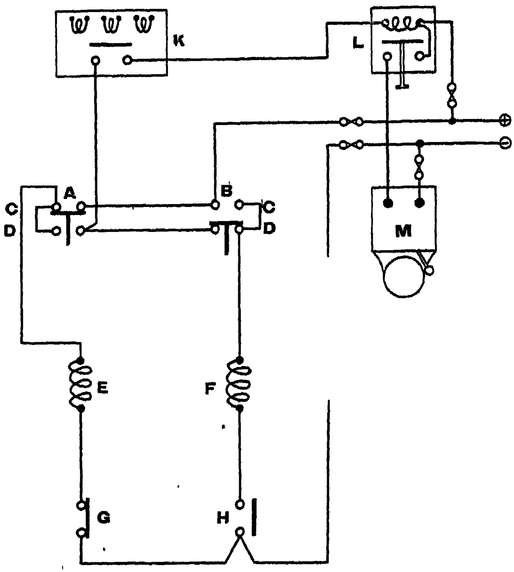


FIG. 13. TRIPPING CIRCUITS FOR DUPLICATE BUSBAR SWITCHGEAR

A—Push button for tripping front breaker
B—Push button for tripping rear breaker
C—"Hand" tripped position
D—"Automatic" tripped position (held by spring in this position)
E—Shunt trip coil (front busbar breaker)
F—Shunt trip coil (rear busbar breaker)
G—Auxiliary contact, closes when breaker closes (front busbar breaker)
H—Auxiliary contact, closes when breaker closes (rear busbar breaker)
K—Fault (protective) relay closes circuit when operated
L—Bell alarm relay (hand resetting)
M—Alarm bell (operates on automatic tripping only)

Diagram shows front busbar breaker being hand tripped (rear breaker open. See "between breakers" interlock)

electrical interlocking of the two breakers and synchronizing circuits, are shown in Figs. 39 and 42.

Isolating Devices. Although the circuit is opened

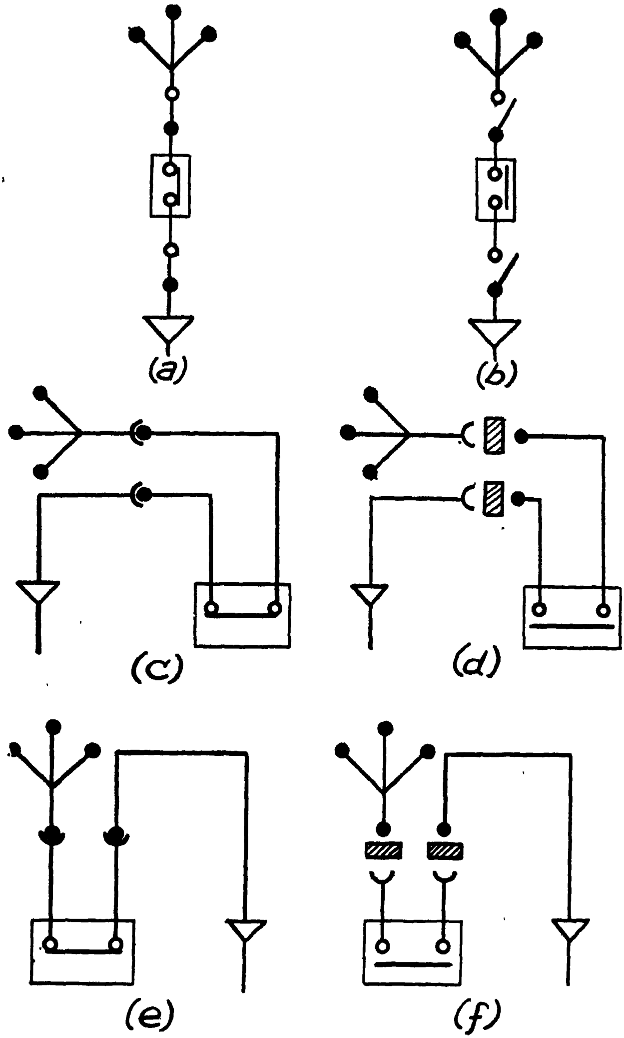


FIG. 14. ALTERNATIVE METHODS OF ISOLATION

and the current interrupted by a circuit breaker, it is necessary to isolate the latter from the rest of the circuit on both sides before inspection, cleaning, test operations or repairs are attempted. Two methods of isolation are in use—

By isolating switches, which are physically separate from the circuit breaker, the latter remaining fixed in position. This method is used on non-draw-out types of switchgear.

By isolating plugs and sockets in which the breaker itself forms the moving link. The circuit-breaker terminals constitute the movable contacts, which engage with fixed contacts. This may be termed the draw-out method of isolation. The circuit breaker is isolated by bodily withdrawal from the circuit in a vertical or horizontal direction.

The above alternative methods are illustrated by single line diagrams in Fig. 14 ; (*a*) and (*b*) is the isolating switch method. The vertical draw-out method is shown at (*e*) and (*f*) whilst the horizontal draw-out method is indicated at (*c*) and (*d*).

Method No. 2 has an overwhelming advantage over method No. 1, in that there is never any doubt as to whether a switch or circuit breaker is properly isolated and safe to work upon.

The use of air-break isolating switches on sheet steel cubicle type switchgear is illustrated in Fig. 15. A hand operating gear controls the circuit breaker whilst the isolating switches are operated from the back of the cubicle by an insulated pole terminating in a hook which fits an eye on the isolating switch blade. The same type of isolating switch is employed in the duplicate busbar cubicle shown in Fig. 16. A solenoid operating gear controls the circuit breaker at the front of the cubicle. The isolating switches are controlled by a hand operating gear at the back of the cubicle. An

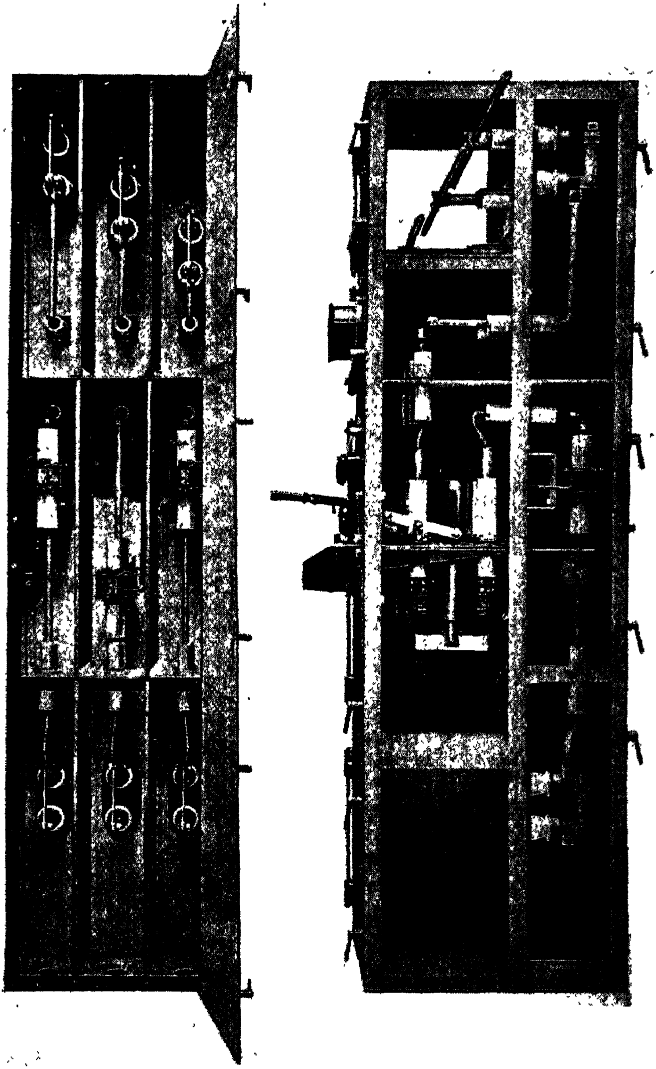


FIG. 15. POLE-OPERATED ISOLATING SWITCHES IN CUBICLE-TYPE SWITCHGEAR

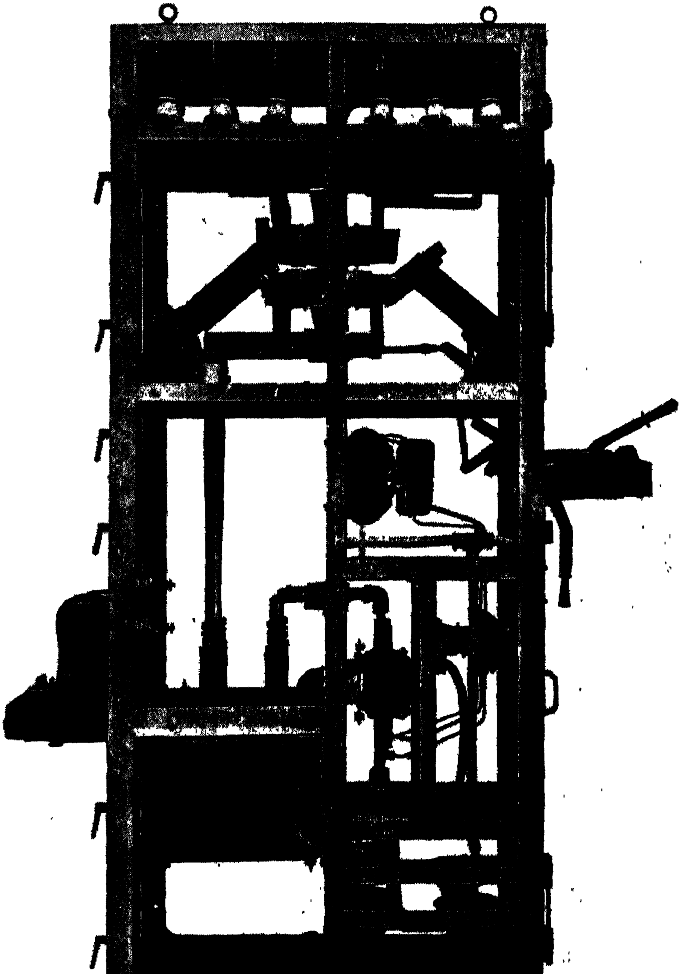


FIG. 16. LEVER-OPERATED ISOLATING SWITCHES IN CUBICLE-TYPE SWITCHGEAR

example of rocker type isolating switches is shown in Fig. 17, which illustrates an outdoor sub-station. Figs.

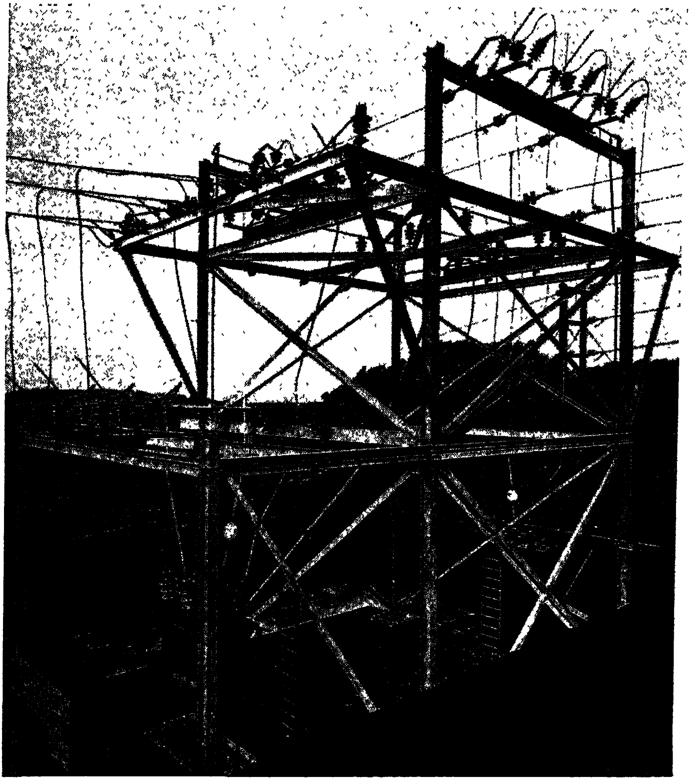


FIG. 17. ROCKER TYPE ISOLATING SWITCHES IN OUTDOOR SUB-STATION

34 and 35 show a rocker type isolating switch fitted with earthing contacts.

The rotary type of isolating switch similar to that shown in Fig. 2, but with pin type insulators, is

frequently used on outdoor type switchgear. Hoods are provided for protecting the contacts from snow and sleet.

Figs. 18 and 19 illustrate the use of the draw-out method of isolation in which the breaker is withdrawn in a vertical direction. The circuit breaker is raised and lowered by two vertical screwed pillars housed in the supporting frames of the switchgear unit. Rotation of the pillars is obtained by a pair of bevel wheels operated by a handle from the front of the switchgear unit. The breaker is carried by two brackets, each of which is fastened to a lifting nut. Translatory motion of the lifting nut is produced by rotation of the screwed pillars. Fig. 18 shows the circuit breaker fully plugged into contact with the rest of the circuit. After the circuit breaker has been lowered to the isolated position, the weight can be taken off the lifting nuts by hand-operated catches, two of which are fitted on each side supporting frame. The breaker is shown in the isolated position in Fig. 19.

Self-aligning split sockets constitute the breaker terminals. The sockets engage with fixed plugs located in insulating bushings which are shrunk into the spout castings. The latter project downwards from the underside of the busbar and instrument transformer chambers. Vertical draw-out metal-clad switchgear units, in which the raising and lowering gear is motor driven, are illustrated in Figs. 28 and 31.

Switchgear, employing the horizontal draw-out method of isolation is shown in Figs. 20, 21, 23, and 24. Fig. 20 illustrates a medium duty truck type cubicle in which the circuit breaker is carried on a truck. The latter runs on horizontal rails, located at floor level, and withdrawal is effected by hand as shown. A heavy current truck type cubicle, with the fixed housing removed, is shown in Fig. 21. Withdrawal of the truck is assisted by a rack and pinion operated from the front

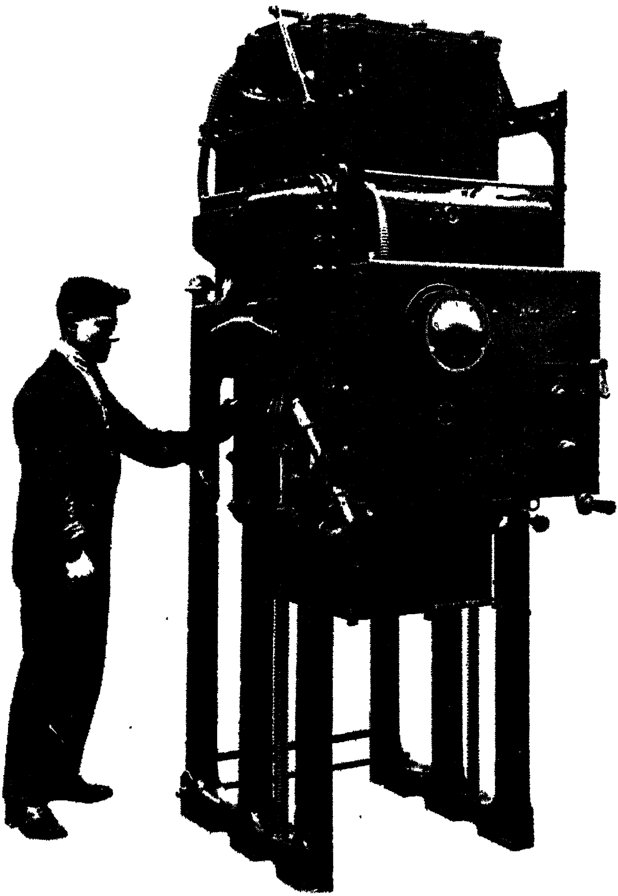


FIG. 18. VERTICAL DRAW-OUT METHOD OF ISOLATION
(Circuit breaker plugged in)

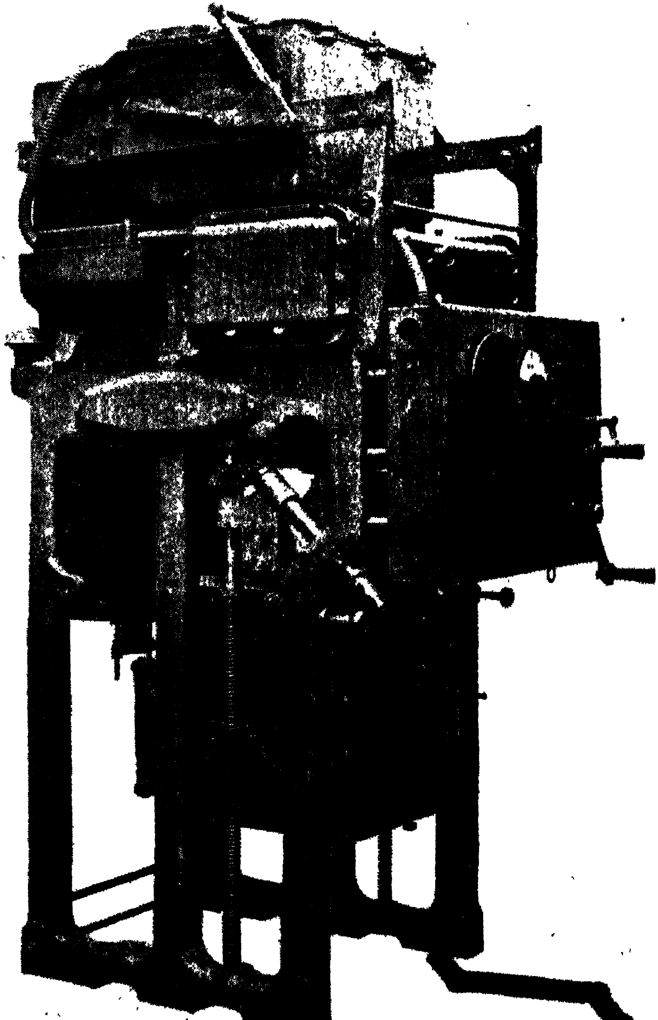


FIG. 19. VERTICAL DRAW-OUT METHOD OF ISOLATION
(Circuit breaker isolated)

of the truck. The plugging members used in the medium duty truck type cubicle are round plugs and sockets, whereas parallel finger type contacts are employed in the heavy current truck type cubicle. Horizontal draw-out metal-clad switchgear is illustrated in

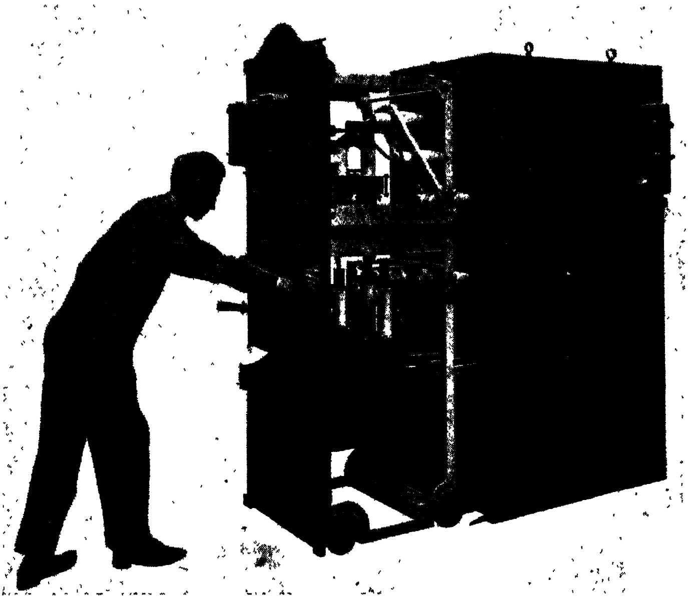


FIG. 20. HORIZONTAL DRAW-OUT METHOD OF ISOLATION
(Circuit breaker isolated)

Figs. 23 and 24. The circuit breaker is withdrawn by a rack and pinion gear, a rack being located on the upper face of each side supporting frame.

The methods of isolating voltage transformers are similar to those employed for circuit breakers. In the case of the switchgear shown in Figs. 18, 19 and 28 the transformer tank runs on horizontal rails at the top

of the switchgear unit. The transformer is isolated by withdrawal along the rails.

Raising and lowering of the voltage transformer by

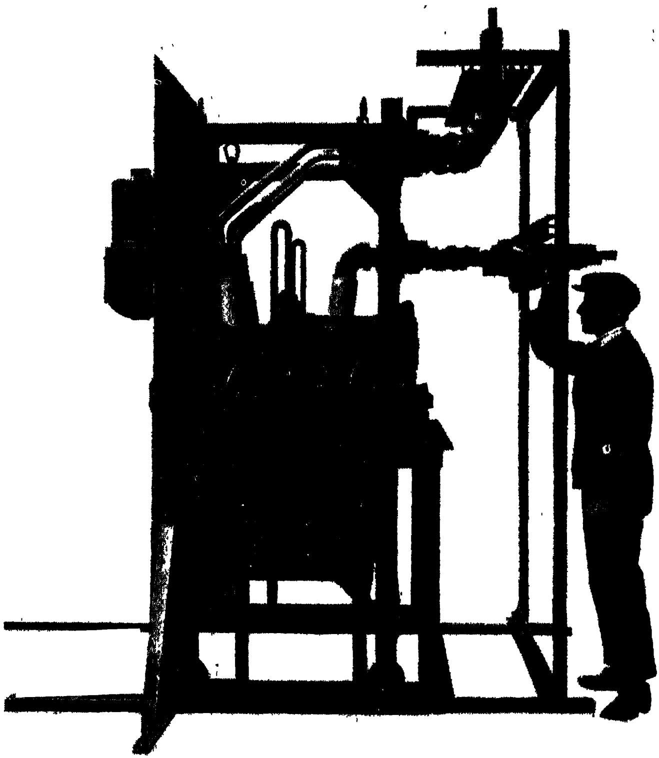


FIG. 21. HORIZONTAL DRAW-OUT METHOD OF ISOLATION
(Circuit breaker plugged in)

means of a wire rope winch is employed on the vertical draw-out metal-clad switchgear illustrated in Fig. 31.

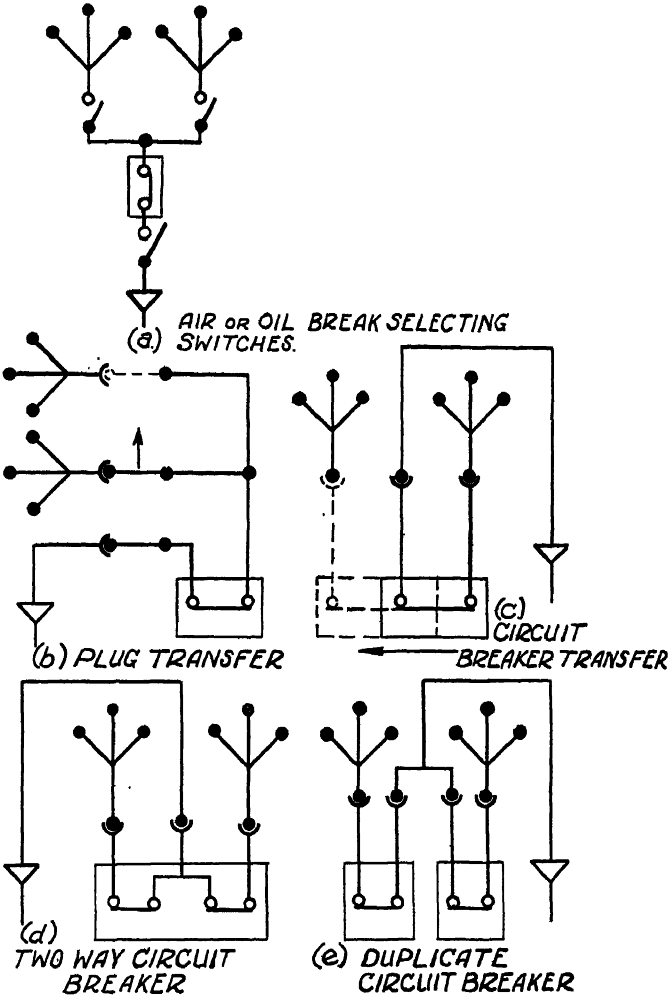


FIG. 22. ALTERNATIVE METHODS OF BUSBAR SELECTION

A handle at the front of the switchgear operates the winch by means of a worm and wheel. The transformer tank slides on vertical guides.

Busbar Selecting Devices. Where duplicate sets of busbars are employed, some method of transferring the

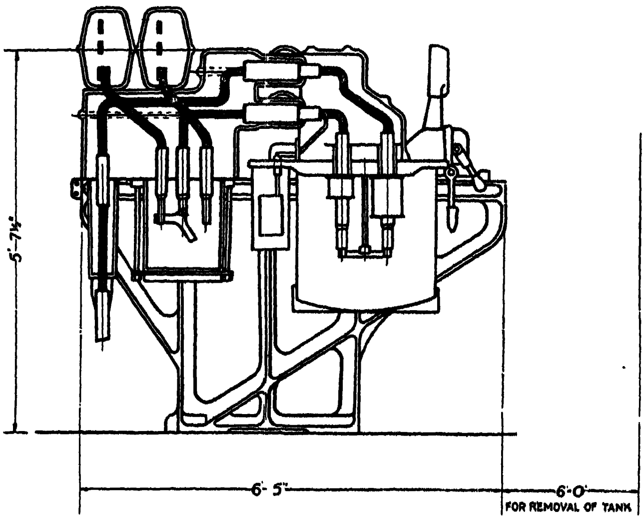


FIG. 23. OIL-IMMERSED SELECTOR SWITCHES

circuits from one set of busbars to the other must be provided. The following methods are in use—

1. Air or oil-immersed selector switches.
2. Plug transfer.
3. Circuit-breaker transfer.
4. Two-way circuit breakers.
5. Duplicate circuit breakers.

The principles involved in the above alternative methods are shown by the single line diagrams in Fig. 22. Air-break selector switches are illustrated in Fig. 16. The use of oil-immersed selector switches is

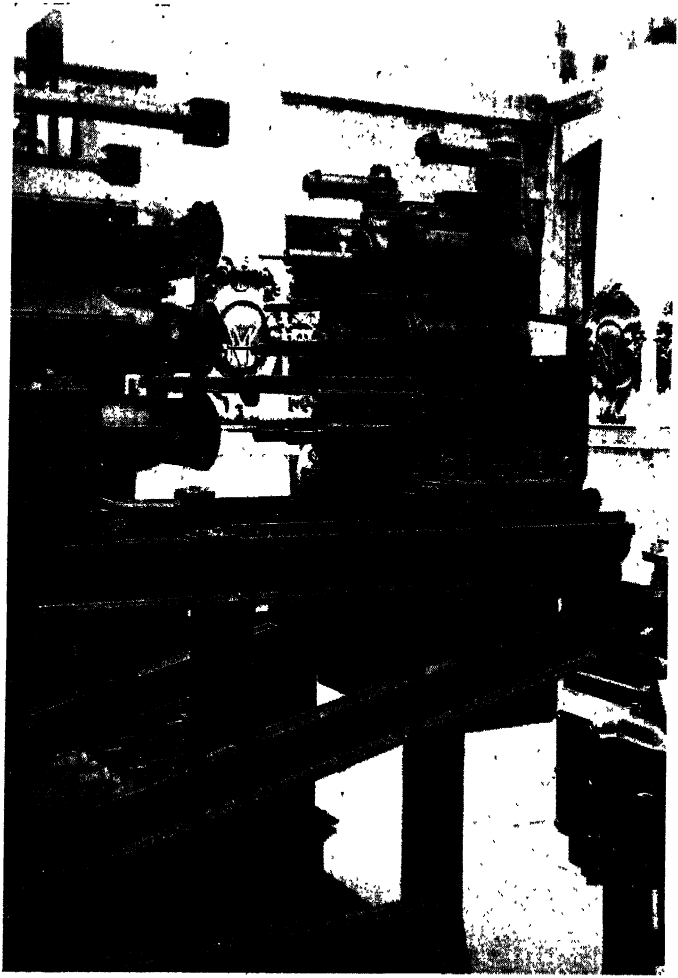


FIG. 24. PLUG TRANSFER METHOD OF BUSBAR SELECTION

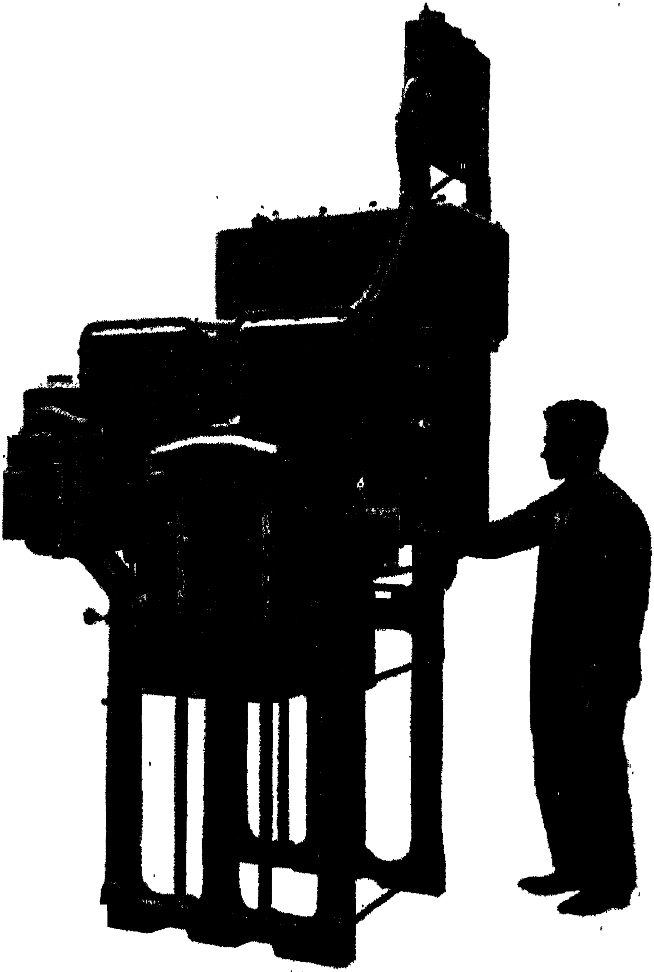


FIG. 25. CIRCUIT-BREAKER TRANSFER METHOD OF BUSBAR SELECTION
(Circuit breaker on front busbars

shown in Fig. 23 which illustrates a horizontal draw-out metal-clad switchgear unit.

Where the isolating plugs and sockets are also used for busbar selection, either method 2 or 3 may be employed. Fig. 24 illustrates the plug transfer method. Each terminal of the circuit breaker on the busbar side is provided with two fittings to which plugs can be fitted at will. Only one removable plug is provided for each phase of the circuit breaker. Selection of the busbars is accomplished by opening the breaker, racking it out and changing over the plugs. The circuit breaker can then be racked into circuit again on the other set of busbars.

Busbar selection by the circuit breaker transfer method is shown in Figs. 25 and 26. The circuit breaker is first lowered to the isolated position and then pushed over on the horizontal rails of the supporting carriage. By raising the breaker it is plugged on to the other set of busbars. Fig. 25 is a half rear view of a vertical draw-out switchgear unit with its circuit breaker plugged on to the front set of busbars. The circuit breaker is shown plugged on to the rear set of busbars in Fig. 26.

A vertical draw-out metal-clad switchgear unit employing a two-way circuit breaker for busbar selection is illustrated in Fig. 27. The circuit breaker is shown completely withdrawn from the unit. Two complete breakers are accommodated in one tank with the centre set of terminals common to both breakers.

The use of duplicate circuit breakers for busbar selection is shown in Fig. 28, which illustrates a vertical draw-out super-power station metal-clad switchgear unit with motor operated circuit breakers. The rear circuit breaker is shown removed from the unit, whilst the front circuit breaker is fully plugged into circuit.

Two-way breakers and duplicate breakers offer a

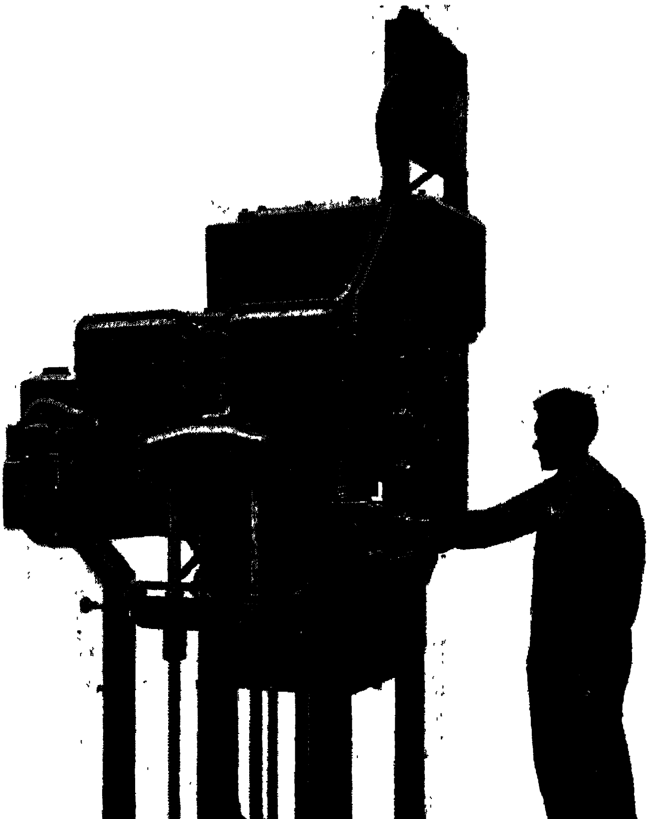


FIG. 26. CIRCUIT-BREAKER TRANSFER METHOD OF BUSBAR SELECTION
(Circuit breaker on back busbars)

great advantage over the other methods of busbar selection in that this operation can be effected from the control room. This results in rapid change over of circuits and unified control of all switching operations.

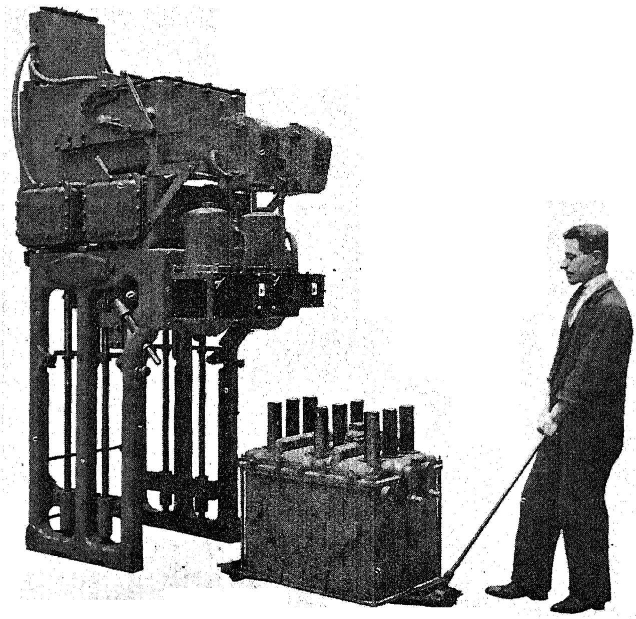


FIG. 27. TWO-WAY CIRCUIT-BREAKER METHOD OF BUSBAR SELECTION

Proper interlocking arrangements must be provided, but these will be dealt with later.

With air or oil break isolating switches a busbar coupling switch must be used if it be desired to transfer generator and feeder circuits from the main set of busbars to the auxiliary set without opening the circuit

breakers. The following procedure must be adopted. First close the bus coupling switch and note that it must not be reopened until the transfer operations have been completed. The auxiliary busbars are now

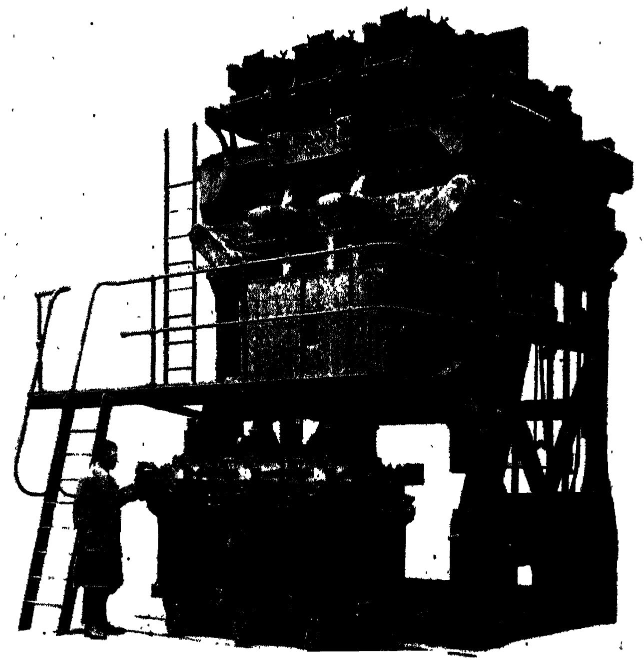


FIG. 28. DUPLICATE CIRCUIT-BREAKER METHOD OF BUSBAR SELECTION

alive, and all the generators, which are to be transferred, can be connected to the auxiliary busbars by the second set of isolating switches on the appropriate panels. The feeders are next transferred by a similar operation. Open the first set of isolating switches on the generator

panels, thus disconnecting the generators from the main set of busbars. The feeder circuits can now be disconnected from the main busbars by a similar operation. Complete transference is accomplished by opening the busbar coupling switch. Other feeders and generators can be transferred in a similar manner after closing the busbar coupling switch, but this latter must not be closed until the two sets of busbars are in synchronism.

Where two-way breakers or duplicate breakers are used, a separate busbar coupling switch is not required, but the same general procedure must be adopted in transferring circuits from one set of busbars to the other.

With the plug transfer and breaker transfer methods of busbar selection, it is not possible to transfer circuits without opening and isolating the circuit breakers. In changing over more than one generator, the second and followng generators must be re-synchronized with the auxiliary busbars before transfer can be completed. A busbar coupling switch is also necessary.

INSPECTIONAL OPERATIONS

Periodical inspection, cleaning, testing and repairs are necessary, and the switchgear should be provided with facilities for carrying out these operations in safety.

Switches, Circuit Breakers, and their Tanks. Oil tanks have to be lowered fairly frequently and occasionally it is necessary to completely remove a circuit breaker from the switchgear. The apparatus required for carrying out these operations varies with the type of switchgear.

A portable tank raising and lowering device is shown in Fig. 29. The platform, on which the oil tank rests, is raised and lowered by racks and pinions which are, in turn, driven by a hand-operated worm and wheel.

Other mechanisms, such as ratchets and pawls or wire rope winches may be employed. This type of tank lowering device is generally used on cubicle, truck, and medium-sized horizontal draw-out types of switchgear.

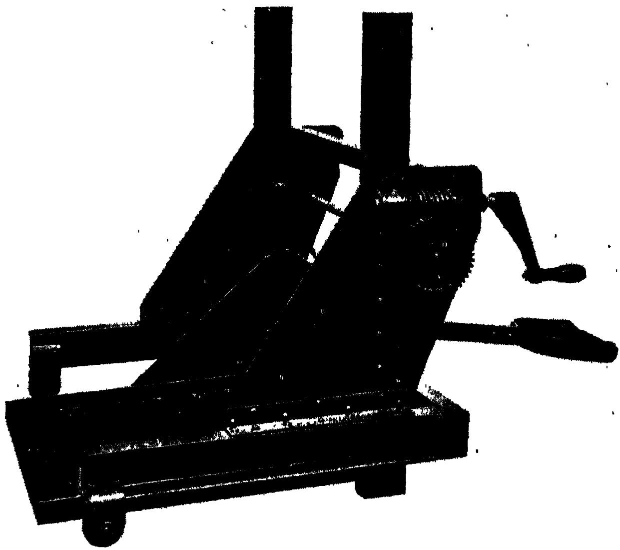


FIG. 29. PORTABLE TANK LOWERING DEVICE

The bogie is wheeled under the circuit breaker and the platform raised until the tank rests on it. After removing the nuts from the tank bolts the tank can be lowered clear of the circuit breaker and completely withdrawn, leaving the internal portions of the circuit breaker accessible for inspection, etc.

Heavy indoor circuit breakers and all outdoor circuit breakers (up to 88,000 volts rating) are generally fitted with a wire rope lowering winch, which is an integral

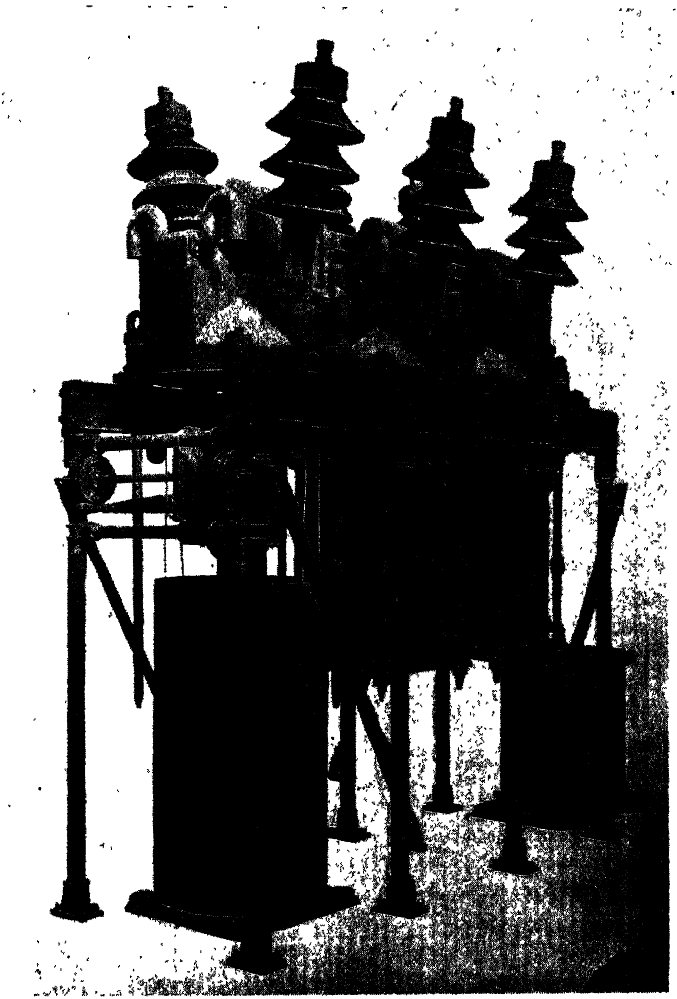


FIG. 30. WIRE ROPE WINCH METHOD OF TANK LOWERING

part of the supporting framework. A frame-mounted outdoor oil circuit breaker fitted with a wire rope tank lowering gear is illustrated in Fig. 30. Outdoor circuit breakers rated at 110,000 volts and upwards are generally mounted directly on the floor. Access to the oil tank is given by a manhole either in the circuit breaker top plate or at the side of the tank.

On the above types of switchgear, the removal of a complete circuit breaker is not an easy matter. The circuit breaker on horizontal draw-out metal-clad switchgear usually has to be lifted off the supporting frames by a crane or pulley block tackle. Vertical draw-out type metal-clad switchgear is the only type of gear from which the complete circuit breaker can be removed without the aid of external raising and lowering gear.

Fig. 31 illustrates a duplicate busbar vertical type metal-clad switchgear unit. The circuit breaker has been lowered on to a bogie and completely removed. The same raising and lowering gear is used for isolation, and lowering of the circuit breaker or tank. After the circuit breaker has been isolated as described on page 22 and illustrated in Fig. 19, the side catches are engaged with the top plate of the circuit breaker. Removal of the tank fastenings allows the tank to be lowered away from the circuit breaker, which remains on the catches. The tank is received on a portable bogie and withdrawn from the switchgear as illustrated in Fig. 32. Motor-driven raising and lowering gear is fitted on the larger metal-clad switchgear units shown in Figs. 28 and 31. In these cases, a limit switch is fitted at each end of the travel. The limit switches are automatically operated by one of the side lifting nuts and prevent over-travel independently of the operator. Figs. 40 and 41 show the control and interlocking circuits for the motor-driven raising and

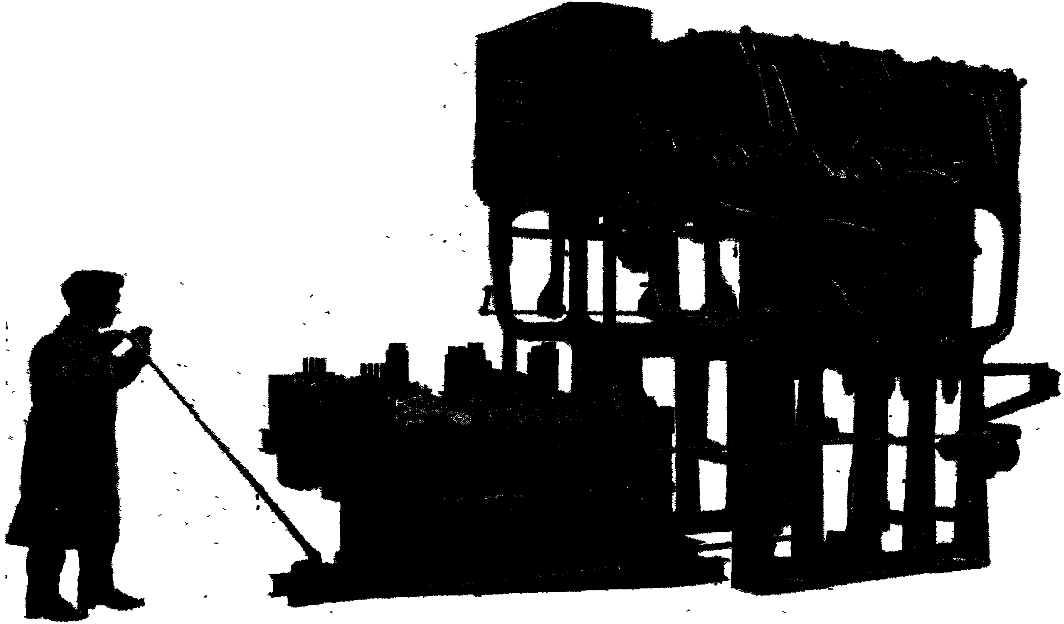


Fig. 31. Removal of Circuit Breaker from Vertical Metal-clad Switchgear

lowering gear on duplicate busbar metal-clad switchgear.

Safety Shutters and Doors. The live side of air-break isolating and busbar selecting devices is shielded

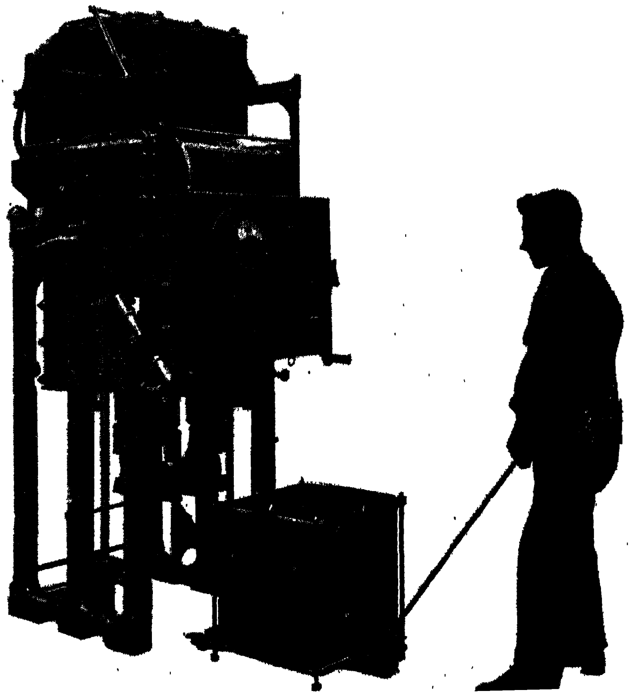


FIG. 32. REMOVAL OF TANK FROM VERTICAL METAL-CLAD SWITCHGEAR

by safety shutters and doors. In the case of draw-out switchgear it can be easily arranged for the safety

NOTE—Positions of locking plates are such that left-hand shutter is free to operate. Right-hand and centre shutters are shown locked in the closed position.

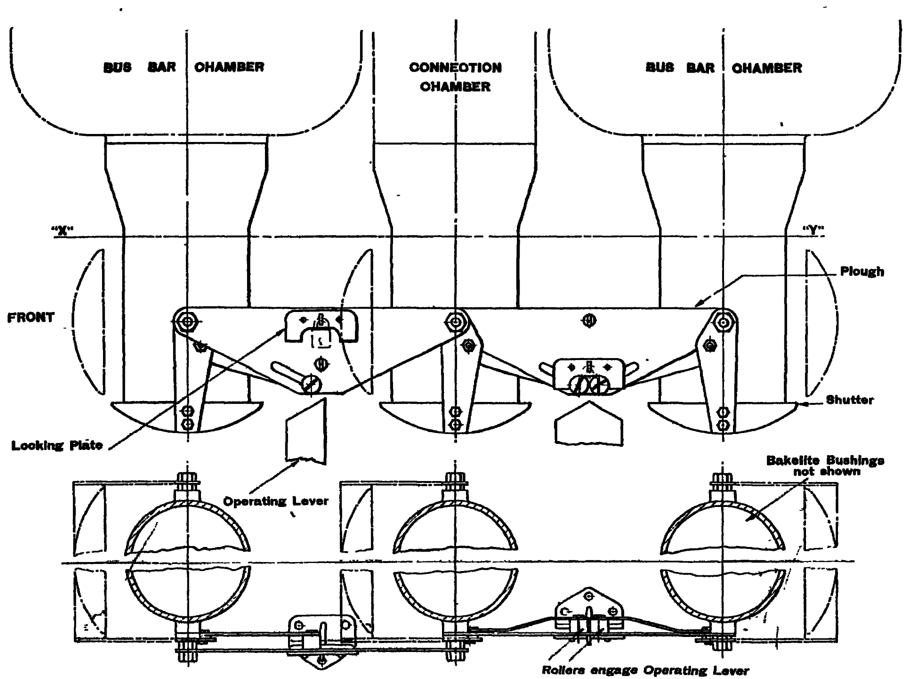


FIG. 33. SAFETY SHUTTER MECHANISM

shutters to be automatically operated by the moving portion of the switchgear. A typical safety shutter mechanism is illustrated in Fig. 33. This mechanism is used on vertical type metal-clad switchgear, operation of the shutters being effected by vertical steel plates which are fixed to the circuit breaker top plate. These plates can be clearly seen in Fig. 31. The shutters can be padlocked in the closed position.

In the case of pole-operated air-break isolating switches as shown in Fig. 15, the height of the switches is relied upon for safety against inadvertent contact. The door of the isolating switch compartment must be opened before the switches can be operated. Increased safety is obtained where the isolating switches are gang operated by a mechanism internal to the cubicle as in Fig. 16. The mechanism is controlled by a hand operating lever located at the back of the cubicle, and it is not necessary to open a door.

Oil-immersed isolating and busbar selecting switches are usually employed on metal-clad switchgear as exemplified by Fig. 23. The switches are completely shielded, but it is essential that the tank should not be lowered until the switchboard is totally dead.

Earthing Devices. Where work has to be done on apparatus or circuits, it is essential that they should be properly earthed before the work is started. In the case of a feeder that can be made alive from either end, the earthing should be carried out at both ends. It is always possible that a live circuit may be earthed in error and, hence, it is desirable that the earthing operation be carried out through an oil circuit breaker. The practice of earthing by means of an oil circuit breaker is not universal. On non-draw-out switchgear the earthing is effected by the isolating switch blades which pass through the open position into earthed contacts. A variation of this method is illustrated in

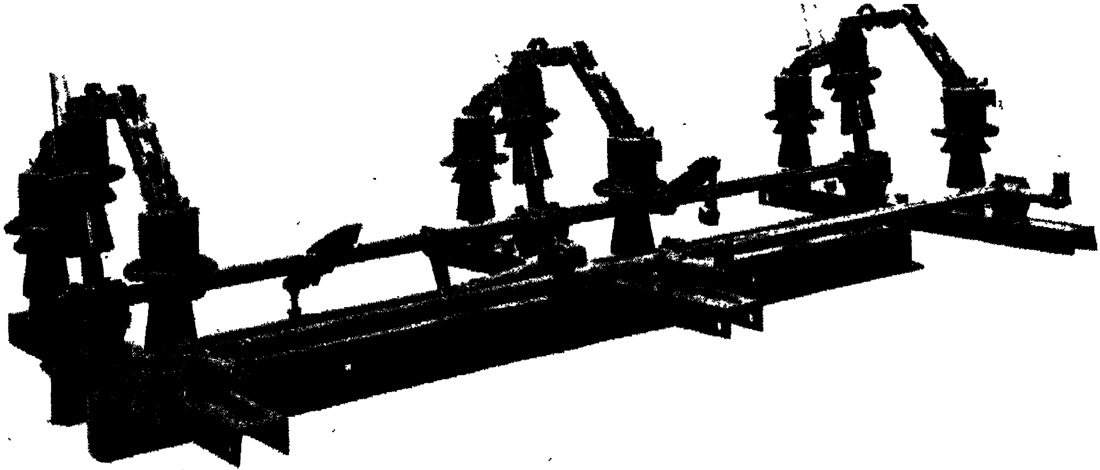


FIG. 34. EARTHING CONTACTS ON OUTDOOR ROCKER TYPE ISOLATING SWITCH
(Earthing contacts open)

Figs. 34 and 35, which show an outdoor rocker type isolating switch fitted with earthing arms, which swing over into the vertical position and earth the cap of the pin-type insulators. Fig. 34 shows the isolating switch closed with the earthing switches open. In this case the earthing arms are coupled to the main operating shaft so that they close when the isolating switch opens and vice versa. The earthing switches are shown closed in Fig. 35.

The two alternative methods of earthing are shown in principle by Fig. 36, which illustrates the application to vertical metal-clad switchgear ; (*a*) shows the direct method of earthing, i.e. not through a circuit breaker. The method of earthing through a circuit breaker is illustrated at (*b*).

INTERLOCKING DEVICES TO SECURE CORRECT SEQUENCE OF SWITCHING AND INSPECTIONAL OPERATIONS

Absolute safety and reliability can only be obtained by carrying out the switching and inspectional operations in the correct sequence. Interlocking devices are fitted to switchgear in order to force this sequence against human impulses. The following fundamental conditions should be satisfied by such interlocking arrangements.

1. It must not be possible to open an isolating or busbar selecting device until the circuit breaker has been opened, or, in the case of a selecting device, until the selecting device has been "by-passed."

2. Access to the circuit breaker terminals or lowering of the oil tank must not be possible until the isolating devices on each side of the circuit breaker have been opened. The "live" side of isolating and selecting devices should be automatically screened to prevent inadvertent contact by switchboard operators.

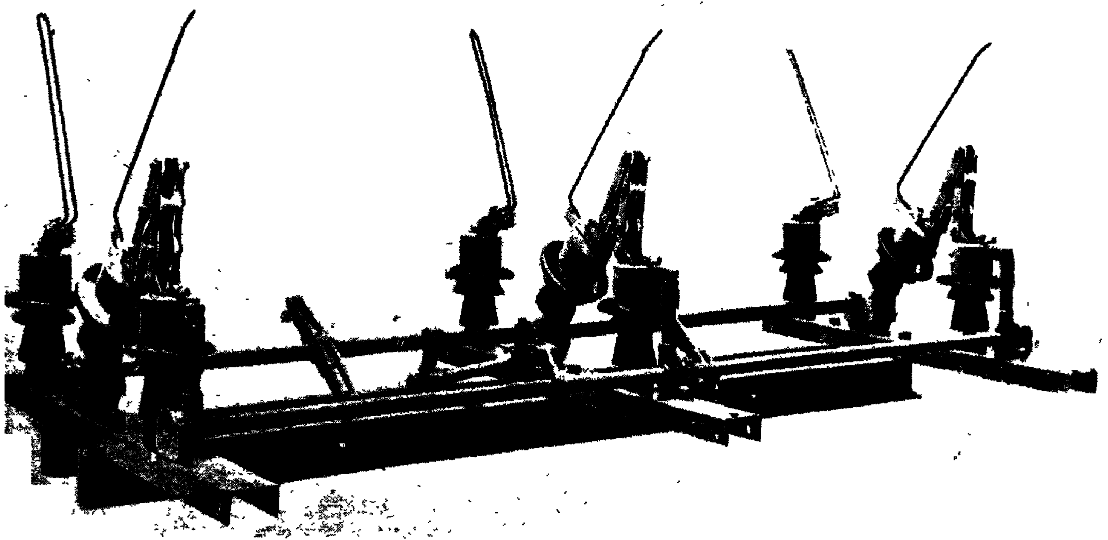


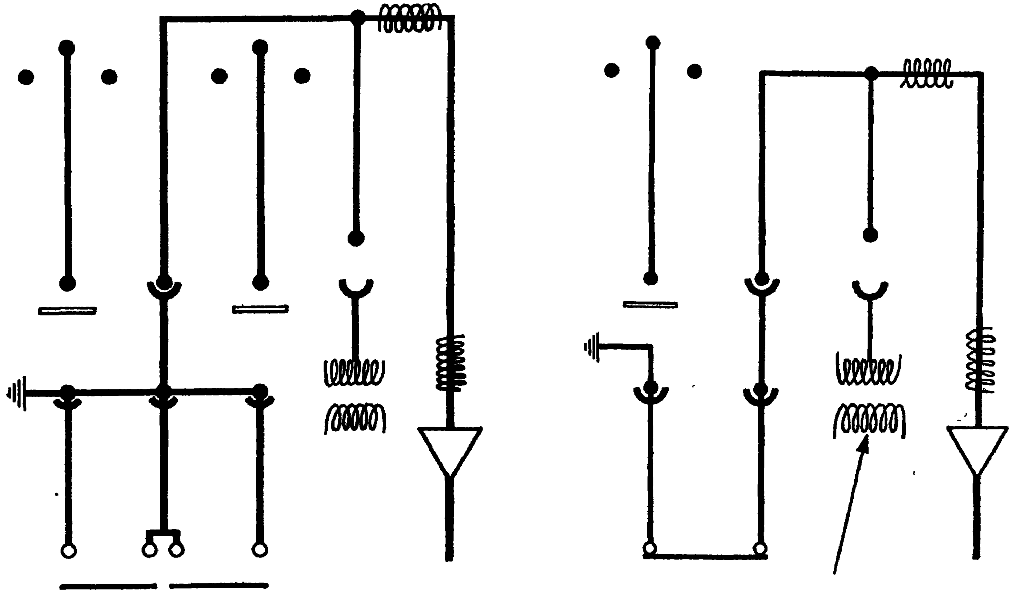
FIG. 35. EARTHING CONTACTS ON OUTDOOR ROCKER TYPE ISOLATING SWITCH
(Earthing contacts closed)

3. Circuits or apparatus, on which work has to be carried out, should be earthed by the switchgear before such work is attempted. It is preferable to carry out the earthing operation by an oil circuit breaker.

4. Reversal of the above operations must only be possible in the reverse sequence.

The above remarks should be borne in mind when operating switchgear which fails to completely satisfy the above conditions. Complete interlocking is an easier problem on draw-out switchgear than on the non-draw-out variety. The most common operating mistake has been to interrupt current on the isolating or selecting devices. To prevent this occurrence, the isolating switch operating gear or cell door must be interlocked with the circuit breaker mechanism. These interlocks usually take the form of rods or levers which act as mechanical locks or bolts for the mechanisms and doors. To prevent access to the circuit breaker until the isolating switches have been opened, the operating mechanism or door for the latter must be interlocked with the circuit breaker cell door. This interlock is not infallible in the case of pole-operated isolating switches, as the cell door for the latter may be opened, thus allowing access to the circuit breaker without the isolating switches being pulled out. Where a separate tank lowering device is employed, the above interlocks prevent lowering of the oil tank until the circuit breaker has been isolated. Again, a circuit breaker with pole-operated isolating switches is an exception.

In the case of draw-out switchgear, the circuit breaker racking out or lowering gear is interlocked with the circuit breaker mechanism. On the horizontal draw-out type of metal-clad switchgear, the oil tank is mechanically interlocked with the racking out gear to prevent lowering of the tank until the circuit breaker is fully isolated. In the case of vertical draw-out



(a) (b)

Fig. 36. Alternative Methods of Earthing

(b) Voltage transformer isolated

metal-clad switchgear, the oil tank is inherently interlocked with the raising and lowering gear because the circuit breaker is supported by the tank during raising and lowering operations and the circuit breaker cannot be held on the side catches until it is in the isolated position. A mechanical interlock, to prevent closing of the circuit breaker, until it is fully plugged in, is shown in Fig. 37. At " A " the isolated position, the interlocking lever releases the tripping lever and the circuit breaker can be closed. At " B " the roller lever engages with the vertical guide causing the interlocking lever to lock the tripping lever. This action prevents the circuit breaker from being closed until the plugs have properly engaged, i.e. the circuit breaker must be in the operation position " C." This interlock also trips the circuit breaker should any attempt be made to lower it whilst in the closed position.

Where two-way circuit breakers or duplicate circuit breakers are employed for busbar selection the circuit breakers must be interlocked to prevent both being closed simultaneously. In the case of manually-operated circuit breakers a mechanical interlock must be provided. An example is illustrated in Fig. 38.

The interlock comprises a bracket (located between the operating mechanisms), which carries two pivoted sector-shaped plates capable of movement in a horizontal plane. These plates (see Fig. 38 *a*) are arranged to engage with corresponding slots in the handle mechanisms when the latter are in the " open " position. Each plate is provided with holes to receive a locking pin, the *outer* holes being so disposed that with one plate engaging with its slot a controlling lever can lock the plates in position so that only one circuit breaker can be closed at any one time. By adjusting the plates and lever, so that the inner line of holes coincides, the circuit breakers can be closed

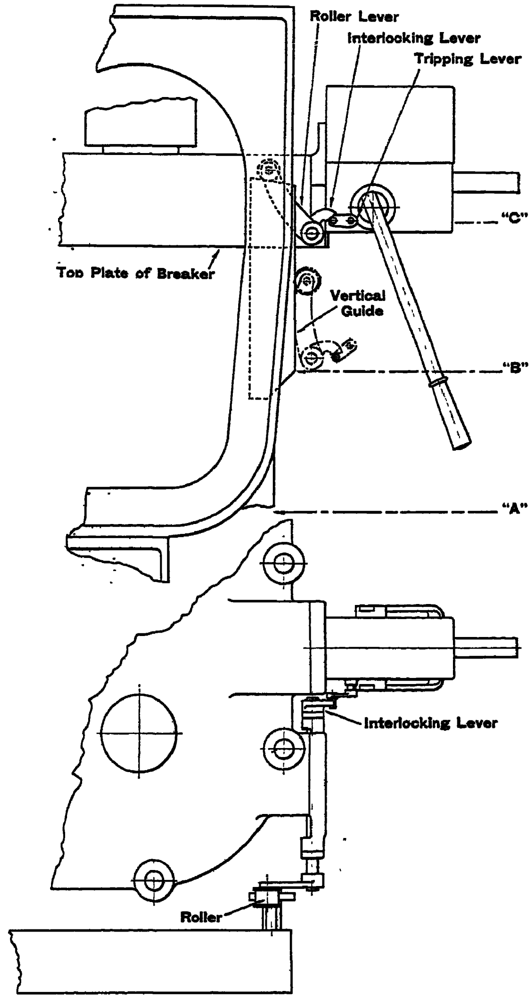


FIG. 37. MECHANICAL INTERLOCK BETWEEN CIRCUIT BREAKER AND LOWERING GEAR

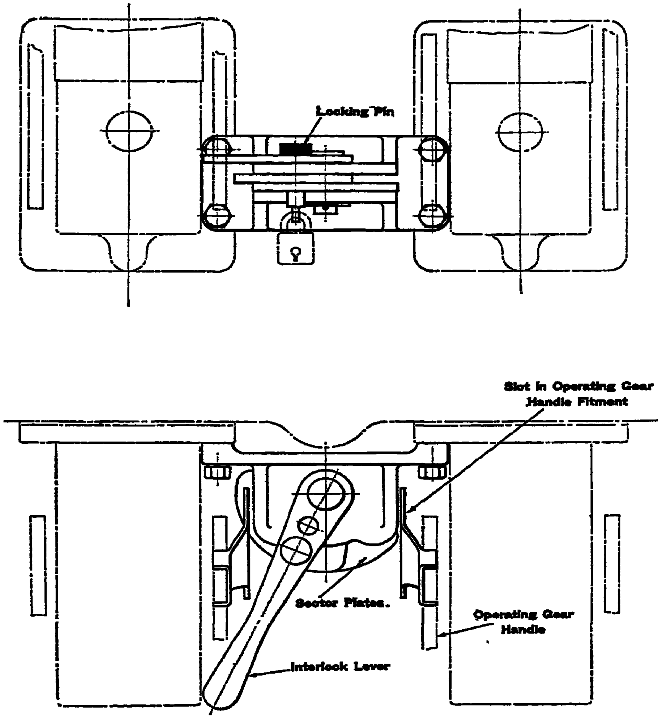
simultaneously. The locking pin is drilled in order that the controlling lever (see Fig. 38 *b*) may be padlocked in any one of the three positions.

Electrically-operated circuit breakers can be interlocked electrically by taking the closing circuit of one circuit breaker through an auxiliary contact on the other as shown in Fig. 39. The closing of switch *M* removes the interlock and lamp *N* lights up. It should be noted that the closing and synchronizing plugs are not interchangeable. The diagram shows the front breaker closed and also the position of synchronizing plugs.

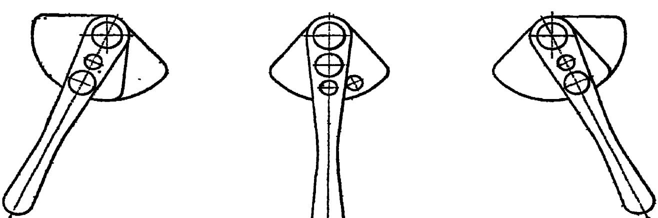
In the case of motor-driven raising and lowering gear, it must be interlocked with the circuit breaker operating mechanism to prevent withdrawal or insertion of the circuit breaker unless it is in the open position. A diagram of the interlock is shown in Figs. 40 and 41. Where two-way circuit breakers or duplicate circuit breakers are used, it is desirable to interlock the synchronizing and closing circuits to prevent closing a circuit breaker on to the wrong set of busbars during the process of synchronizing. A typical diagram is shown in Fig. 42, which also shows the connections for synchronizing between busbar sections.

Where the plug transfer method of busbar selection is employed, a mechanical interlock should be provided to prevent a partial change over of plugs. Fig. 24 clearly shows a simple interlock, which prevents the circuit breaker being "racked in" unless all three plugs are in either the top or bottom set of plug orifices in the circuit breaker hood. The interlock consists of a hinged cover, which must be folded back to cover the set of empty orifices, before the circuit breaker can be "racked in." One plug is shown left in the top set of orifices to illustrate the interlock.

Switchgear should be examined periodically and the



MECHANICAL INTERLOCK BETWEEN BREAKERS "A"



MECHANICAL INTERLOCK BETWEEN BREAKERS "B"

FIG. 38. MECHANICAL INTERLOCK BETWEEN CIRCUIT BREAKERS

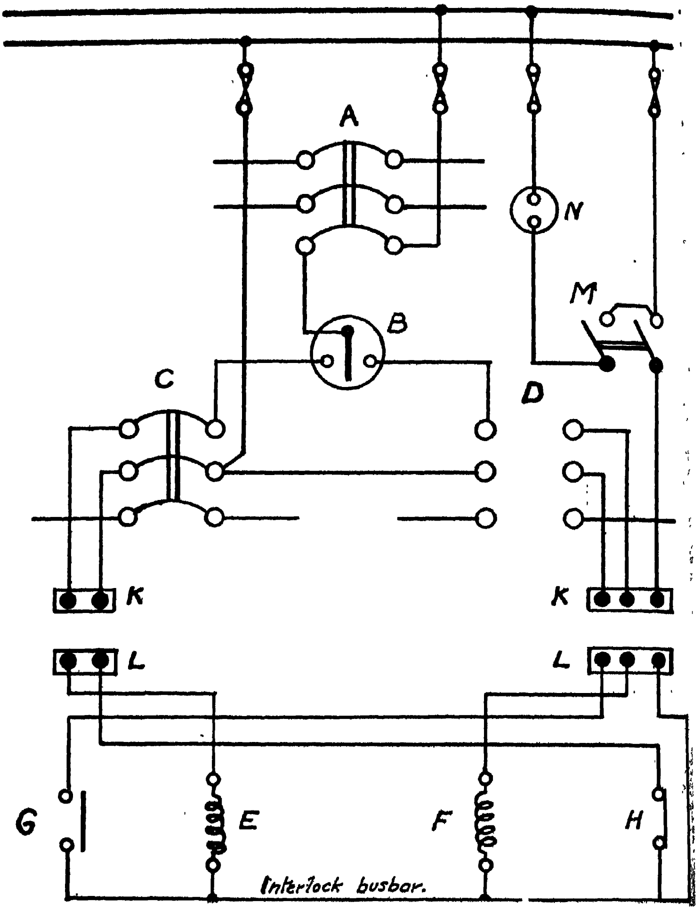


FIG. 39. ELECTRICAL INTERLOCK BETWEEN CIRCUIT BREAKERS

A—Synchronizing plugs and sockets (see Fig. 42)
B—Control switch
C—Closing plugs and sockets (front busbars)
D—Closing plugs and sockets (rear busbars)
E—Contactor operating coil (front busbars)
F—Contactor operating coil (rear busbars)
G—Front breaker auxiliary switch (closes when breaker opens)
H—Rear breaker auxiliary switch (closes when breaker opens)
K—Terminal board (control panel)
L—Terminal board (unit)
M—Interlock switch
N—Interlock lamp
NOTE. Solenoid circuits and the necessary plugs and sockets are omitted for clearness

operation of all parts tested. Unlike rotating machinery, the operating parts of switchgear only render intermittent service and, hence, require to be tested

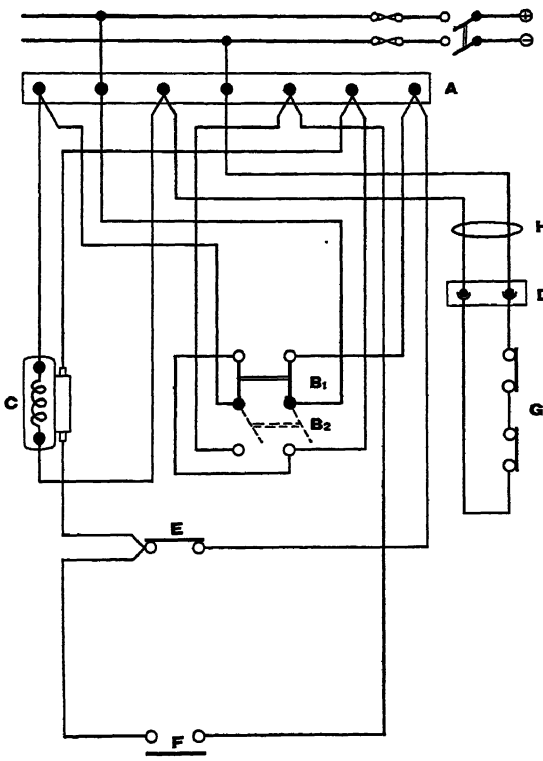
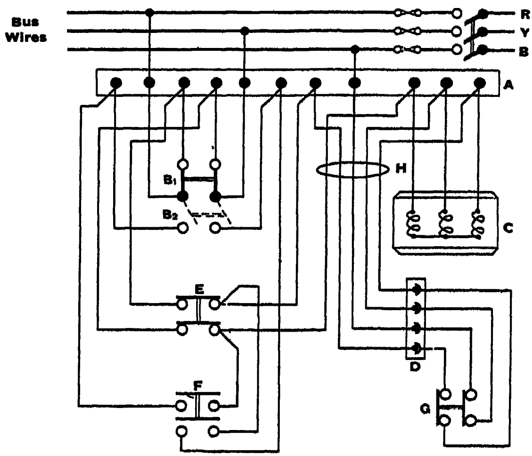


FIG. 40. ELECTRICAL INTERLOCK BETWEEN DIRECT CURRENT LOWERING GEAR AND CIRCUIT BREAKERS (DUPLICATE BUSBARS)

A—Terminal board
B_1—Starting switch. "Up" position
B_2—Starting switch. "Down" position
C—Motor
D—Two-point plug (on manually operated units only)
E—Top limit switch
F—Bottom Limit switch
G—Oil breaker auxiliary contacts (open when breaker closed)
H—Trailing cable (on manually operated units only)

regularly to ensure that all is in order when service is required of them. This is particularly necessary in the case of protective gear, which only operates at



(FIG. 41. ELECTRICAL INTERLOCK BETWEEN ALTERNATING CURRENT LOWERING GEAR AND CIRCUIT BREAKER (SINGLE BUSBAR)

A—Terminal board
B_1—Starting switch. "Up" position
B_2—Starting switch. "Down" position
C—Motor
D—Four-point plug (on manually operated units only)
E—Top limit switch
F—Bottom limit switch
G—Breaker auxiliary contacts (open when breaker closed)
H—Trailing cable (on manually operated units only)

long intervals. Circuit breakers require special attention as soon as possible after they have interrupted a short-circuit.

CARE OF FIXED AND MOVABLE CURRENT CARRYING CONTACTS

The contact surfaces of all bolted joints in busbars and connections should be tinned and, in compressing the joint, an uneven distribution of pressure can be

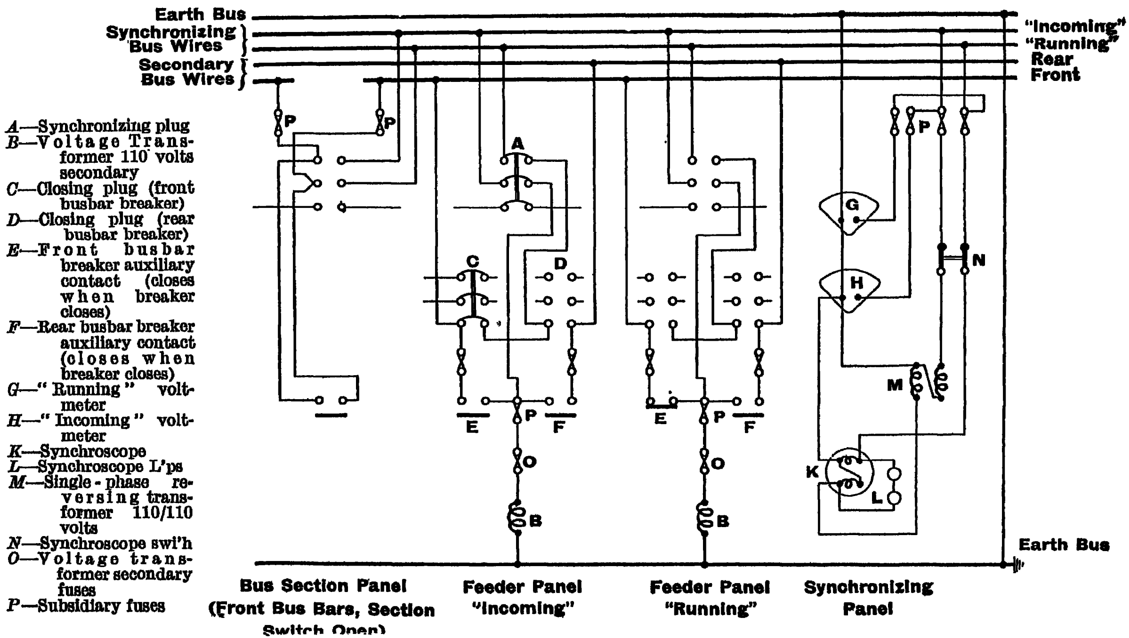


FIG. 42. ELECTRICAL INTERLOCK BETWEEN CLOSING AND SYNCHRONIZING CIRCUITS

Diagram shows position of plugs and switches when synchronizing a feeder on the front busbars

avoided by tightening up the bolts in rotation, a little at a time, until full pressure is obtained on the contact surfaces.

Joints whose surfaces are exposed to the atmosphere, even if only for short periods at long intervals, should be covered with a film of vaseline to prevent oxidation after the contact surfaces have been cleaned. Examples of such joints are the plugs and sockets of draw-out switchgear and the contacts of air-break switches and circuit breakers.

The contact surfaces of oil-immersed switches and circuit breakers must be cleaned before putting them into commission. Metal polish will remove dirt and oxide. Under normal service conditions, the contact surfaces are protected from oxidation by the surrounding oil. Dirt and oxide cause localized heating and the consequent excess of temperature softens steel backing springs and the hard brush copper of laminated brush type contacts. Replacement of these parts is the only remedy in such a case. Failure to see that a clean metal-to-metal contact was obtained before the switch or circuit breaker went into commission has been the cause of unsatisfactory service by switches and circuit breakers of all makes.

Continuously rated switch and circuit breaker contacts are, broadly, of two types, namely, the "finger" type with continuous contact surfaces and the "laminated brush" type with divided contact surfaces. A preliminary check on the intimacy of contact can be made by a 0·002 in. feeler gauge, which should not enter the edges of the contact surface. This test, however, does not guarantee satisfactory contact over the whole area of contact surface. A thin film of prussian blue, mixed with oil, and rubbed over the contact surface will indicate "high spots," on closing the switch or circuit breaker and, as the contact is a sliding

one, a good idea of the distribution of contact will be given by the appearance of the high spots.

With the switch or circuit breaker in the closed position, finger type contacts should be tested by slightly lifting each finger to ascertain whether there is even distribution of pressure. No adjustments should be necessary on a new switch or circuit breaker, but in the case of a finger, where there is uneven contact across the face, it requires twisting by a pair of pliers. Care must be taken to avoid damage to the contact face itself.

If it should be necessary to " grind in " finger type contacts, on no account must emery powder be used, as the grains become embedded in the softer copper. A mixture of fine pumice powder and oil forms a good abrasive. After contacts have been " ground in," care must be taken to wash away all traces of the pumice powder.

In the case of switches and circuit breakers which are fitted with brush type contacts, it is necessary to watch that the operating mechanism is correctly adjusted to give the proper pressure on the contacts when the circuit breaker is in the closed position. Fig. 43 illustrates how the proper bedding of the separate leaves of the brush depends on the contact pressure. Each lamination is a unit carrying current, and it is essential for the face of the contact block to be smooth in order that the brush may spread correctly to give a good area of contact.

Any high spots, as shown up by the blue and oil test, can be scraped with a hard scraper, but particular care must be exercised or the brush will be ruined. Brush-type contacts should never be " ground in " with an abrasive powder, as the latter gets between the leaves of the brush.

Circuit breakers are provided with two sets of contacts, one set (main contacts) for carrying the normal

current continuously without undue heating and a second set (arcing contacts) for the specific purpose of dealing with the arc, which is drawn when the breaker interrupts current. The arcing contacts are given a "lead" on the main contacts so that the latter are well open before the former separate. On closing the circuit breaker, the arcing contacts make before the main contacts. This transfers the current from the

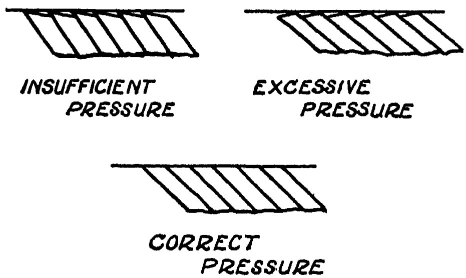


FIG. 43. BEDDING OF BRUSH TYPE CONTACTS

main to the arcing contacts. Brush typo contacts are not suitable for service as arcing contacts. The formation of an arc between arcing contacts inevitably produces "beading" and "pitting" of the contacts. All projections should be removed by a smooth file after heavy rupturing duty has been performed by the circuit breaker. Finger type main and arcing contacts are shown in Fig. 44.

At 6600 volts, where the values of short-circuit current become high, the contact burning becomes serious and substantial arcing contacts must be provided. A point of special importance is the *manner* of contact separation. A difference of opinion exists on this question. Some engineers prefer the contacts to slide off each other, i.e. the contact faces keep in the same plane. With this method, the area of contact

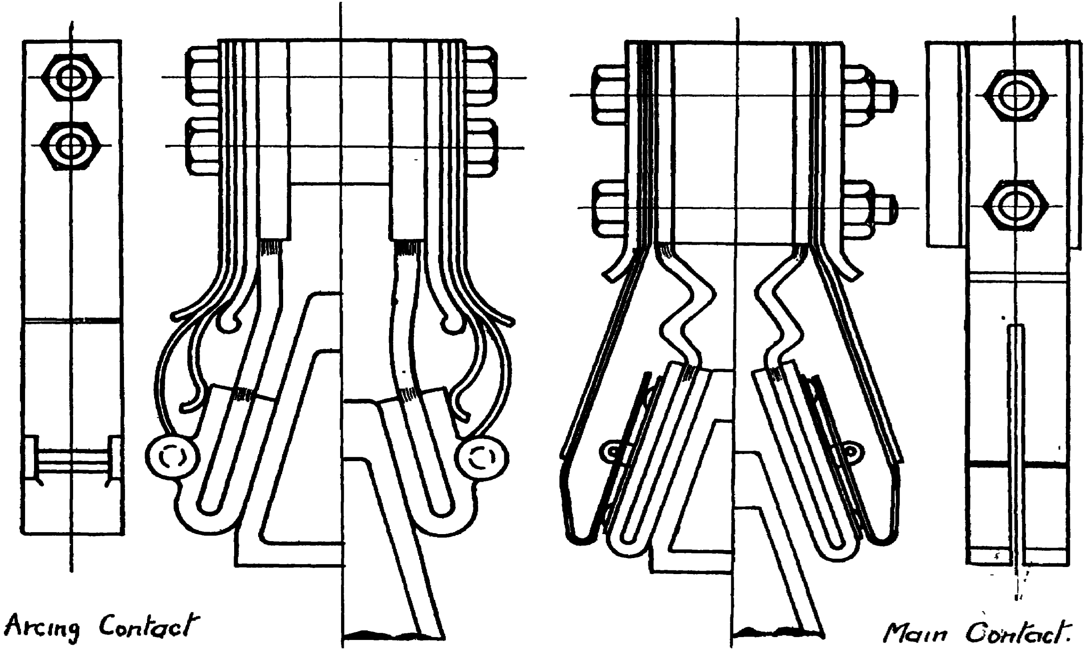


FIG. 44. FINGER TYPE ARCING AND MAIN CONTACTS

gradually diminishes until, at the moment of contact separation, nothing but a line contact exists. It is claimed that the "beading" and "pitting" is thus kept clear of the contact face. This results in the root of the arc being confined to the tips of the arcing contacts and, as the current density increases up to a very high figure indeed at the moment of contact separation, there is, in the author's opinion, a grave danger of "welding in" at high values of short circuit current.

The arcing contact in Fig. 44 has a combined sliding and butt action. During the initial portion of the opening stroke, the wedge slides along the fingers until the backing springs are unstressed. After this point the whole of the wedge leaves the fingers, there being no diminution of contact area at any part of the stroke.

A further point of importance is the mutual attraction of the finger contacts, when heavy currents are flowing. This action is beneficial up to the point of separation, but after this point the fingers must be prevented from pulling together. The arcing contacts illustrated are restrained by being definitely attached to the steel backing springs.

It should be borne in mind that arcing contacts are consumable details and the cleaning up process should not be carried too far in an effort to avoid replacements, but spare contacts should be held in stock. The care of arcing contacts cannot be over-emphasized as neglect may lead to "welding in" of the contacts under short circuit conditions and burning of the main contacts.

Where cable connections have to be made to the terminal studs of a switch or circuit breaker, care should be taken to avoid forcing the studs round when tightening up the surface nuts. Two spanners should always be used and turned in opposite directions so that there is no resultant turning moment on the terminal stud.

The earth connection of the switchgear should be checked to see that all supporting framework is in good contact with the earth bar and that the latter is actually in good metallic connection with the station earth plate.

CARE OF INSULATION

The surface condition of insulating supports and bushings and the general condition of insulating oil must be examined periodically to detect any signs of deterioration, which should be remedied as soon as possible.

Two types of solid material are in general use for insulating the live parts of high tension switchgear, namely, laminated varnish-paper products and porcelain. The former type of material is commonly termed "bakelite," due to the use of a synthetic resin varnish of the bakelite class as a bonding agent.

Plastic insulating materials (compounds) are used for filling metal-clad switchgear chambers. They are poured whilst in a molten state, but, even when cold, they never set solid in the true sense. There is a growing practice of using heavy oils in current transformer chambers to allow easy access for future modifications. Circuit breaker and voltage transformer tanks are filled with transformer oil.

The resistance of laminated varnish-paper bushings to moisture depends entirely on the external coat of finishing varnish, which is baked to give a smooth uniform surface. This surface finish must be preserved, especially at the ends where moisture can gain access to the layers of paper and, very slowly, travel along by capillary action. Should any portion of the paper become exposed, by accidental damage to the surface finish, then such portions must be given six coats of clear air-drying insulating varnish at the first opportunity. Each coat of varnish must be allowed to dry thoroughly before applying the next. Exposed portions

of the bushings on new switchgear are usually covered with a protective wrapping such as cotton tape and wax (or vaseline covered with grease paper and black adhesive tape). Laminated varnish-paper bushings, which are kept in stock or are otherwise out of commission and liable to mechanical damage, should be vaselined and covered with grease paper and black adhesive tape. When removing wrappers from this class of bushing, any adhering matter must not be removed by an abrasive material. Hot transformer oil, applied on a clean cloth, should be used.

A combination of dirt and moisture on the surfaces of insulating bushings causes local discharges (or corona) which attack the varnish and will even attack (much more slowly) the glaze of porcelain insulators. On this account, it is essential that the exposed surfaces of bushings and supports should be cleaned periodically. This trouble assumes serious proportions in stations where condensation, due to large variations of temperature, is considerable. Under tropical conditions, indoor type varnish paper bushings should not be used. The cloths used for cleaning this type of bushing must be of a strong, firm fabric with a velvet-like surface in order to avoid abrasion of and deposition of loose fibres on the bushing surfaces.

For outdoor service, varnish-paper bushings are always sealed with a petticoated or flanged porcelain insulator at the end exposed to the weather. Good quality porcelain is impervious to moisture, even when unglazed, but the outside surfaces are invariably glazed in order to get a smooth surface that will collect as little dirt as possible. Outdoor porcelain insulators get a certain amount of cleaning by the rain, but, due to the electrostatic field, the glaze becomes "plated" with dirt in a finely divided form. This deposit is best removed by paraffin.

The safety factors with which the oil insulated portions of switchgear are designed can be maintained only by preserving the high electric strength of the oil. This is reduced severely by the following external influences—

1. Ingress of moisture in amounts as low as 0·005 per cent.
2. Ingress of cotton and other fibres which are invariably moisture laden.
3. Scale and impurities from drums, pipes, etc.
4. Excessive heating which causes deterioration.
5. Colloidal carbon liberated by heavy arcing under short-circuit conditions.

The only safeguard is to test oil regularly. Tests for electric strength, moisture, and sludging should be carried out at intervals of not less than three months in the case of circuit breaker oil and six months in the case of oil from instrument transformer chambers and tanks. The breakdown of oil in service never occurs by exceeding the real breakdown stress of pure oil, but by the formation of a bridge of impurities either across an oil gap or along the surface of solid insulating material immersed in the oil. When an electric strength test is carried out on commercial oil, it is its *condition* which is tested and not its *quality*.

Impurities in still oil will gradually settle to the bottom of the tank or chamber by gravity. The best method of removing moisture and solid impurities is to pass the oil through a centrifugal separator, which is merely a speeding up of the natural settling process. In the absence of a centrifuge, the oil can be dried by passing it through a bag of clean dry lime. It should then be filtered to remove any suspended particles. A filter can be made by stretching two layers of finely-woven cotton fabric across the top of a large funnel.

The fabric must have been thoroughly washed, previously, to remove sizing and then dried. To accelerate the filtering process. the oil can be warmed. Dehydration of oil by heating necessitates keeping the temperature at a minimum value of 100° C. for long periods, and is not to be recommended as the oil will be injured.

Moisture can be detected by the copper sulphate, and heating tests. The copper sulphate test consists of adding a small quantity of powdered anhydrous copper sulphate to a sample of the oil in a test tube. If the sulphate turns blue or greenish blue, water is present. The heating test is carried out by rapidly heating a small quantity of the oil in a dry saucer, to a temperature slightly above the boiling point of water. If a crackling noise is heard, water is present.

The above tests will not detect quantities of moisture which are small enough to reduce the electric strength of the oil. A high voltage test is the only sure method. The following table is given as a guide in deciding when an oil is in a satisfactory condition for service.

Kilovolts withstood for one minute	Condition of oil
50	Excellent
40	Very good
30	Good
25	Satisfactory
20	Doubtful
15	Unsatisfactory

The above figures refer to the British Standard test gap of 4 mm. between two spherical electrodes each 13 mm. diameter. For full details of tests and methods of sampling, reference should be made to the B.S.S. No. 148, 1927.

It is preferable to store drums of oil indoors, but if drums are left out of doors care should be taken to lay them on their sides with the bungs downwards.

They should be protected from direct rain or snow by a tarpaulin. All oil in unsealed drums (or in sealed drums, if they have been exposed to the weather) should be tested, the sample being drawn from the bottom of each drum by a " thief."

When a drum of cold oil is taken into a warm station, the bung should not be removed until the oil has reached the temperature of the station, otherwise " sweating " will occur by condensation of moisture on the cold oil surface. The inside of all tanks and chambers should be cleaned and dried before pouring in new oil. This also applies to any vessels used in transferring the oil. Cotton waste must on no account be used for cleaning oil tanks, etc., as cotton and other fibres will be deposited.

Carbon, in a finely divided form, is always liberated during arcing under oil. This forms a deposit at the bottom of the tank, on the operating mechanism and on insulating surfaces. Whenever a circuit breaker has interrupted a heavy short circuit, the tank should be lowered at the earliest opportunity. The arcing contacts should be examined and cleaned up and the carbon deposit cleaned off the mechanism and surfaces of insulators. A test should be taken on the oil and, if not satisfactory, it must be cleaned or replaced with new. This examination of the internal portions of an oil circuit breaker should be carried out every three months as a matter of routine.

The oil levels in all tanks and chambers must be watched and maintained at the correct height, otherwise the factor of safety will be reduced. Fig. 45 is an illustration of the oil dipper type of gauge which is perfectly gas tight. If a tank be withdrawn, it should be covered to prevent ingress of dirt, etc., to the oil. Likewise, the covers of oil chambers should be replaced immediately after filling. A leaky cil joint can never

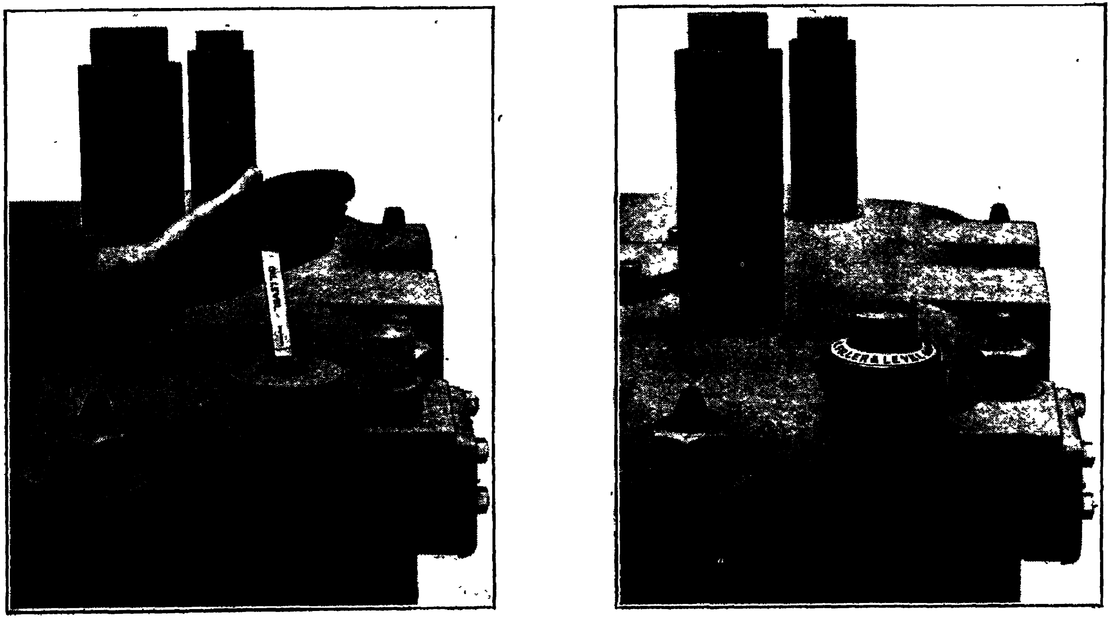
be cured except by stripping it and thoroughly cleaning away all traces of oil before remaking the joint with a new gasket. A good gasket can be made from finely grained cork sheet (Langite) treated on both sides with gold size.

Switchgear, that has been out of commission for some time, should be given a high voltage test before putting it back into service. Before applying the test, all leakage surfaces of bushings should be clean and dry, and the oil should be in good condition. A preliminary test for insulation resistance should always be carried out. Neglect of the above precautions may lead to the injury of perfectly sound insulation. The B.E.S.A. one-minute high voltage test for new switchgear on site, preparatory to putting it into commission, is 2000 volts plus twice the working voltage. This test, together with the one-minute test at the maker's works, is a check on the flashover and one minute puncture voltages. The relationship between the factor of safety during the one minute test and the working factor of safety depends on the time voltage characteristic of the insulation as shown in Fig. 46. An alternative duration test, recently introduced by the B.E.S.A., is preferable for tests, preparatory to putting switchgear into commission. The voltage scale of the curves in Fig. 46 is purely relative, with the B.E.S.A. one minute test voltage taken as 100. The test voltage for the duration test is 60 per cent of the one minute test voltage and is applied for 10 minutes.

In carrying out high voltage tests the following precautions should be taken.

1. Increase the voltage uniformly.

2. Use a sphere spark gap connected in series with a protective resistance. The spark gap and resistance must be connected across the high voltage terminals of the testing transformer, and should be set to discharge at a voltage approximately 10 per cent above the test



(a) (b)

FIG. 45. DIPPER TYPE OIL GAUGE

voltage. A resistance value of at least one ohm per volt of the test voltage should be used.

The first precaution will avoid discharge of the spark gap and so save time. Precaution No. 2 is necessary in order to limit the peak value of the voltage applied to the switchgear. Abnormal values may be experienced due to a peaky wave, high values of capacity, brush discharges or variations in the supply voltage. A spark gap should never be used without a series resistance, otherwise oscillations will be set up when the gap discharges.

CARE OF OPERATING PARTS

The operating parts of switchgear should be examined periodically. All bearings, sliding parts, knuckle joints, pins, etc., should be kept clean and lubricated with a good thin machine oil, sparingly applied. Heavy lubricating oils should *not* be used on account of their tendency to become "gummy," when the operating parts are not in continuous motion, as is the case with switchgear mechanisms. This, together with the accumulation of dirt, may render a mechanism sluggish or even inoperative at a critical moment. Under outdoor conditions, the most satisfactory method of lubrication is by grease cups.

The closing and tripping operations of a switch or circuit breaker should always be checked prior to putting the gear into service. Closing and tripping tests should be carried out with the circuit breaker isolated from the rest of the system. The minimum voltage at which a circuit breaker will close and trip should be tested. A lower limit of 80 per cent and 50 per cent of the normal operating voltage for closing and tripping coils respectively at a temperature of 40° C. is specified by B.E.S.A. At 15° C. these values are approximately 73 per cent and 46 per cent. The coils must operate satisfactorily

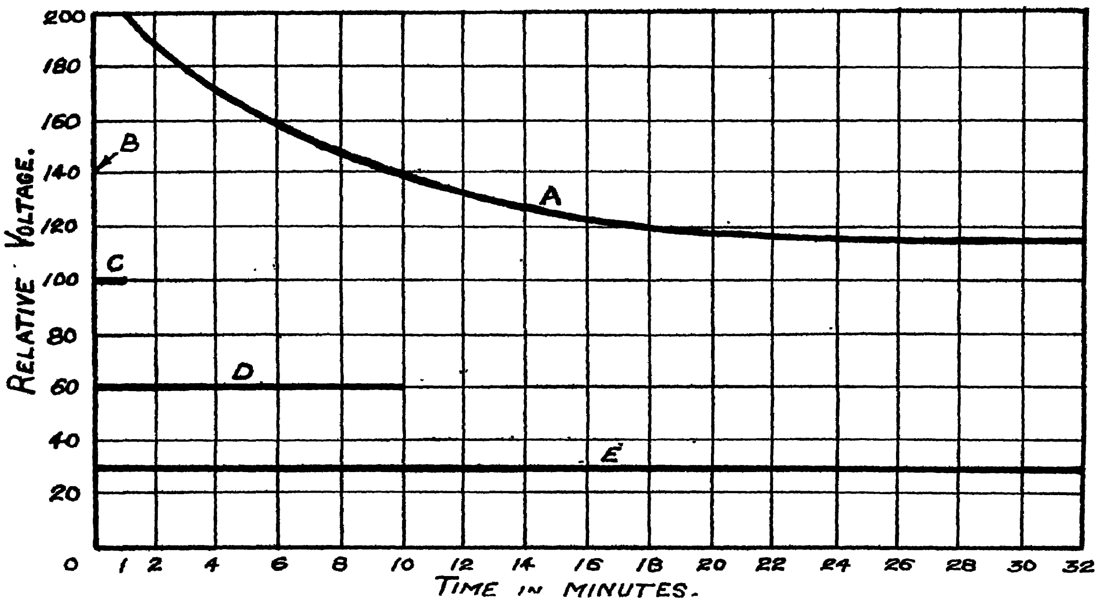


FIG. 46. RELATIONSHIP BETWEEN TEST VOLTAGE AND FACTOR OF SAFETY IN SERVICE

A—Breakdown voltage—time curve.
B—Flash-over voltage.
C—B.E.S.A. one-minute high-voltage test.
D—B.E.S.A. ten-minutes high-voltage test.
E—Working voltage of insulation.

at 10 per cent above the normal operating voltage. During the closing test, the circuit breaker contacts should be inspected to see that full area of contact is obtained with the circuit breaker in its "closed" position. The operating mechanism must be adjusted if full contact area is not obtained. An oil buffered circuit breaker should not be tripped without its oil tank unless temporary buffer springs are fitted. Care should also be taken that the buffers at the end of the closing stroke are correctly adjusted in order to avoid harsh operation on the circuit breaker contacts.

In order to get full efficiency out of the trip coil, it should be adjusted so that the maximum travel is obtained, when tested by hand from the plunger or armature, before the holding-on catch is released. A little travel must be allowed beyond this point to ensure certainty of tripping. When testing the tripping operation of a circuit breaker it should be done from the relay contacts. If the tripping battery consists of primary cells, it should be periodically tested to prevent the voltage falling below the minimum tripping value.

The operation of indicating lamps, alarm bells and semaphores should be checked. In case of trouble, the auxiliary switches on the circuit breaker should first be examined to see that contact is being made.

Every inspectional operation should be checked during periods of inspection, even if all the operations are not required at the time. Interlocking mechanisms should only be checked during periods of partial or complete shutdown when no danger exists in case a mechanism fails to function correctly.

CARE OF PROTECTIVE GEAR

Protective gear is installed for the purpose of—

(*a*) Ensuring continuity of supply to a maximum area of the network.

(*b*) Limiting the amount of damage to faulty apparatus or circuits.

(*c*) Minimizing shock to the rest of the system.

Owing to the intermittent nature of its duty, protective gear should be tested periodically, an initial test being made prior to putting the gear into commission and subsequent routine tests being carried out at least every year.

This question of testing, even yet, does not receive the attention it deserves. Protective gear is frequently installed and put into commission without being tested. The maker's tests on new gear are the initial steps towards satisfactory service, but it should be borne in mind that one incorrect connection, or even a misconception as to the conditions of operation, may render the finest protective gear entirely useless.

The value of earthing resistances should be tested, bearing in mind that the total limiting resistance during an earth fault includes the contact resistance at the earth plate (or pipes). This latter resistance should be checked every six months. The total value of earthing resistance should be low enough to pass sufficient earth fault current to operate any protective device on the system.

The tripping supply for relays should preferably be entirely independent of the supply network to be protected and must be carefully maintained.

A test for continuity and correct connection should be carried out on all small (secondary) wiring by a lamp, bell, or galvanometer testing set and the polarity of all instrument transformers tested with a dry battery and moving coil millivoltmeter using the D.C. "kick" method (see p. 842). After removing all earth connections, insulation resistance and high voltage tests can be carried out. The test voltage should be 2000 volts applied for one minute. All earth connections should

be replaced immediately after the above tests. Space will not allow the inclusion of a schedule of tests to be carried out on all protective schemes, but a few typical examples are given below. The results of all tests should be logged systematically. Satisfactory operation during the initial tests should not be made an excuse for future neglect to carry out tests.

OVERLOAD AND LEAKAGE

Continuity of the secondary circuits can be checked by injecting a single-phase alternating current into the leakage circuit. Approximately one-third of this current should be recorded in each of the three phases. The primary circuits must be open during this test.

Balance can be tested whilst three-phase load current is passing by measuring the current in the leakage relay or trip coil by a low impedance milliammeter. No reading should be obtained or, at any rate, only a few milliamperes. Out of balance may be due to a difference in the ratio or polarity of the current transformers. A polarity error gives double the phase current in the leakage circuit, whereas the out of balance current due to ratio corresponds to the ratio difference.

A *tripping test* on the overload relays or trip coils can be carried out by passing single-phase alternating current through two phases of the primary circuit in series. The leakage relay or trip coil can be checked by passing current through one phase only of the primary circuit.

If it should be necessary to insert an ammeter in any phase of the secondary circuit, it should be remembered that an open circuit will cause the leakage relay to trip and the current transformer concerned will develop a high voltage, the value depending on the primary ampere turns corresponding to the primary current at the time. When a gap is to be made in a

current transformer secondary circuit, care should be taken that the ammeter terminals are securely connected to each side of the joint before the joint is opened.

Trouble may be experienced, where ordinary current transformers are used for leakage protection, due to triple frequency secondary currents in the leakage circuit. This prevents the use of low settings.

CORE BALANCE LEAKAGE AND FERRANTI-HAWKINS

Continuity of the secondary circuit can be tested by a lamp, bell, or galvanometer set.

Balance is checked by connecting a low impedance milliammeter in the secondary circuit whilst three-phase load current is passing. No reading should be obtained.

A *tripping* test can be carried out by passing alternating current through one phase only of the primary circuit. In the case of Ferranti-Hawkins gear, the primary current must pass through one core balance transformer only.

MERZ PRICE BALANCED VOLTAGE

Continuity of pilot circuits can be tested by disconnecting the pilots from the air gap transformers at one end of the feeder. The voltage between the centre and each outer phase should be measured at each side of the break. If four voltages are not recorded, then there is discontinuity either due to broken pilots or loose connections.

Discontinuity of the compensating screen can be checked by disconnecting the screens entirely at both ends and starring them at one end of the feeder. A test for discontinuity can be carried out by lamp, bell, or galvanometer set from one end. No readings should be obtained.

Earthing can be checked with the same connections as for the continuity test by measuring the voltage of each phase to earth at each side of the break. This will show whether one, both, or none of the secondary star points are earthed.

Balance should be tested with heavy straight through current, but this can, generally, only be done at the maker's works. A low impedance milliammeter is connected in series with the pilot wires and the out of balance current measured. A similar test should be conducted on site with three-phase load current flowing. This will not test balance, but is a useful check on polarity and correct connections. Poor insulation of the pilots may also be the cause of a reading on the milliammeter.

The tripping current for earth faults can be determined by passing single-phase alternating current through the primary of one current transformer only.

Inter-phase fault settings can be checked by passing three-phase current into an artificial short circuit located between the two sets of protective transformers. The earth fault setting can be deduced from this test, where it is not desired to earth one phase of the primary circuit. It is 50 per cent greater than the setting obtained on interphase faults.

MERZ PRICE CIRCULATING CURRENT

Continuity of the pilot circuit can be checked by measuring the current flowing in each pilot wire. Continuity of the relay circuit can be tested by crossing two pilots when current should flow in the two corresponding relay coils. This current should be approximately 1·732 times the pilot current, and no current should appear in the third relay coil. Continuity of the third relay coil circuit can be tested by crossing a different pair of pilots.

Balance is checked by measuring the current in the relay circuit. With generator gear there will be no reading, whereas with transformer gear a reading corresponding to the magnetizing current will be obtained. Out of balance may be due to wrong connections or polarity, a difference in ratio or loose connections. On this type of gear it is essential to have low resistance contacts. The balance and continuity tests are carried out with primary load current flowing.

Tripping is tested by passing alternating current through the primary of one current transformer only. This gives the earth fault setting. The interphase fault setting is checked by passing three-phase alternating current into an artificial short circuit located between the two sets of protective transformers.

SPLIT CONDUCTOR AND SELF-BALANCE

Continuity can be checked by testing the secondary wiring with a lamp, bell, or galvanometer set.

Balance is tested by measuring the current in the relays. No reading should be obtained. A break in one split will cause out of balance.

Insulation between splits should be tested by measuring the insulation resistance. The primary circuit must be open during this test.

Tripping can be checked by passing alternating current through one split of each phase in turn.

POLARITY TEST ON INSTRUMENT TRANSFORMERS

The object of polarity markings is to indicate the instantaneous direction of current *output* from the secondary winding corresponding to the direction of current *input* to the primary winding at the same instant. Various polarity markings are in use, but they all virtually allocate the plus and minus marks as

shown in Fig. 47. This simple marking has been shown in order to keep the principles clear. Standard markings as adopted by the B.E.S.A. are given in B.S. Specification No. 81, 1927, which should be consulted.

A method of testing for polarity is shown in Fig. 47. With the connections as shown, the needle of voltmeter

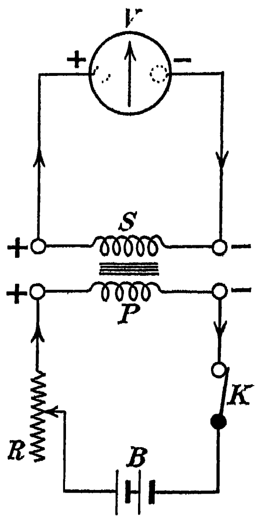


FIG. 47. D.C. "KICK" METHOD OF TESTING POLARITY

V—Centre zero moving coil voltmeter.
P—Primary winding.
S—Secondary winding
B—Dry battery, ½ to 3 volts
R—Variable resistance.
K—Switch.

V should kick over to right-hand side of zero when switch *K* is closed.

The author wishes to acknowledge his indebtedness to Messrs. Ferguson, Pailin, Ltd., for their kind permission to publish all illustrations, except Fig. 24. Permission to publish this illustration was kindly given by The Metropolitan-Vickers Electrical Co., Ltd.

SECTION XIV

IRONCLAD SWITCHGEAR

BY

JOHN M. GOODALL

Chief Switchgear Engineer, British Thomson-Houston Company

SECTION XIV

IRONCLAD SWITCHGEAR

IRONCLAD switchgear may be defined as gear in which all live parts are contained in an earthed metal enclosure. Switchgear of this type for extra high tension duty is covered by the section of this publication dealing with "Super-generating Voltage Switchgear."

The present section refers to ironclad gear for service up to 3300 volts, and having the following applications—

Small power stations.

Station auxiliaries in large power stations.

Factory sub-stations.

General industrial duty.

Surface and underground duty in collieries.

Situations where the atmosphere is laden with dust, such as cement works, flour mills, etc.

Locations where excessive moisture prevails.

For tropical duty where vermin are present.

In each of the above applications back of panel or cubicle type switchgear described in a previous section is unsuitable, and ironclad gear is either preferable or essential.

Take, for example, industrial duty. Conditions of safety render it necessary to protect all live conductors against accidental contact and, further, a minimum of space has to be occupied, since the switchgear is non-productive.

Next, consider colliery duty, where to secure proper safety, conductors must be contained in a flameproof enclosure sufficiently robust to withstand an internal explosion.

Finally, in the case of switchgear for peculiar atmospheric conditions, it is again necessary to enclose the whole of the apparatus, and, in some instances, the enclosure must be compound filled.

These and other conditions obtain in each of the applications mentioned, so that ironclad switchgear has a definite and important field which cannot be filled by open type panel gear.

TYPES OF IRONCLAD GEAR

For the several applications referred to previously, different types of ironclad gear are employed. The more usual types are as follows—

(*a*) Wall-type non-drawout gear.
(*b*) Pedestal type non-drawout gear.
(*c*) Pedestal-type horizontal drawout gear.
(*d*) Drop down vertical plugging gear.

Each of these types is made in industrial and flame-proof models, compound filling being usual on the latter, but optional on the former.

It will be observed the essential differences in these types are first, the method of mounting, i.e. wall or pedestal mounted, and, secondly, the provision or omission of plugging devices which enable the oil circuit breaker to be isolated from the busbars and the circuit.

In regard to mounting it can be assumed that wall-mounted equipments are employed exclusively for the control of individual circuits such as motors or transformers.

Where a number of circuits has to be controlled, then a switchboard is required fitted with busbars, and the oil circuit breakers in this case are mounted on pedestals.

With respect to isolating devices these when provided can take the form of pole-operated links in the case

of non-drawout gear, or plugs and sockets on drawout gear, either arrangement allowing the breaker to be isolated and rendered safe for examination or maintenance work.

While the foregoing sets out the principles which

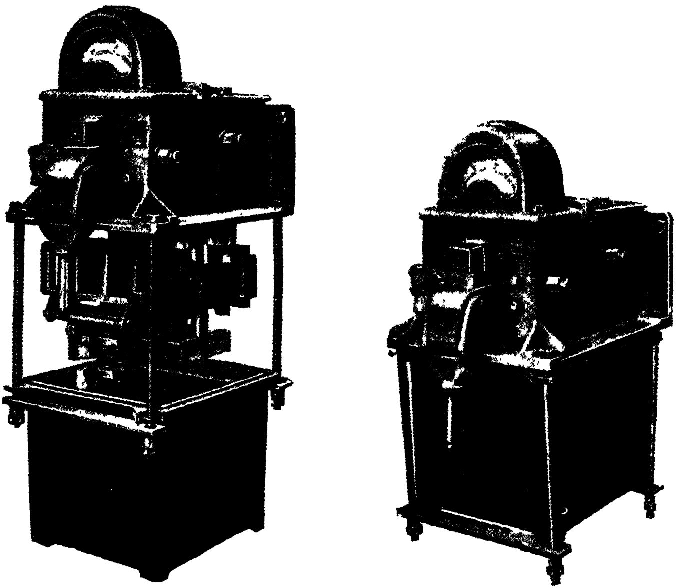


FIG. 1. TYPICAL WALL-MOUNTED OIL CIRCUIT BREAKER

govern the general arrangement of ironclad gear, the physical forms of this gear differ widely, so it is proposed to review each type in the paragraphs which follow.

WALL-MOUNTED IRONCLAD GEAR

A typical wall-mounted ironclad oil circuit breaker rated at 300 amp. up to 3300 volts is illustrated by Fig. 1.

Such a breaker is totally enclosed, dust-proof and damp-proof, and suitable therefore for service in exposed positions, for general industrial service, and for mining service where flameproof enclosure is not required.

The features mentioned are obtained by having wide

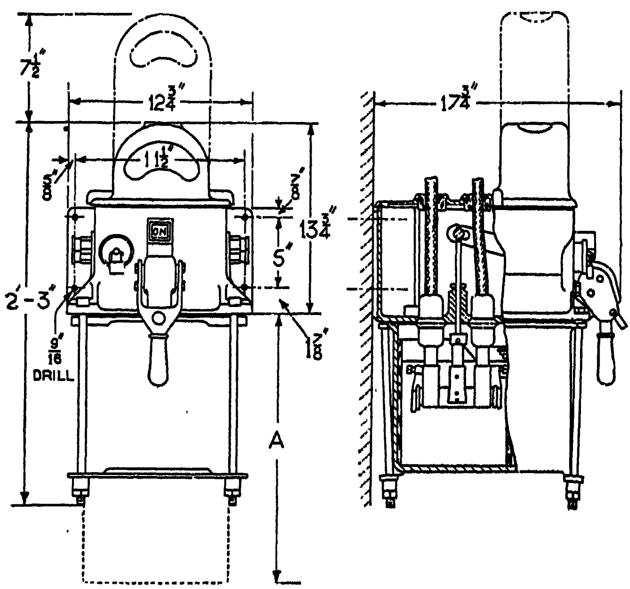


FIG. 1A. SECTIONAL VIEWS OF WALL-MOUNTED OIL CIRCUIT BREAKER

A—22½ in. with tank in lowered position, breaker open or closed.

flanges at the joints between the tank, the ammeter hood, the cable entry and the main frame, all points being fitted with rope packing.

For service up to 3300 volts the overload trip coils and the ammeter are usually of the series pattern, so that current transformers are not necessary. Where a

breaker is employed to control a motor a device is fitted to render the overload releases inoperative when starting, as otherwise the heavy initial starting current would trip the breaker.

For a similar reason the ammeter is fitted with buffer stops, so that the needle will not be damaged by rushes of current equal to several times full load.

Most breakers are fitted with low volt release attachments, which if desired may be interlocked with the

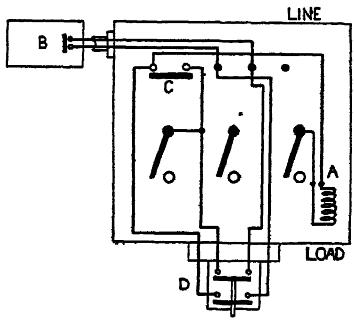


FIG. 2. CONNECTION DIAGRAM FOR OIL CIRCUIT BREAKERS
With under-voltage release arranged for electrical interlocking with motor starter

A—Under-voltage release coil.
B—Starter: Interlocking contacts only bridged when starter is returned to the " off " position.
C—Aux. switch operated by circuit-breaker mechanism; contacts bridged when breaker is closed.
D—D.P. Push button switch, hand-operated, normally open.

motor starter, so that the breaker cannot be closed unless the starter is in the " off " position. The interlocking circuits are shown in Fig. 2.

It will be noted the low volt circuit is completed through auxiliary contacts on the starter, which contacts are only bridged when the starter is " off." In order that these contacts shall not be permanently alive a double-pole auxiliary switch is fitted to the breaker enabling the low-volt release circuit to be

connected to the line side of the breaker prior to closing.

To meet the variety of cabling arrangements breakers of this type have cable entries suitable for three-core paper-insulated lead-covered cables, or three-core bitumen-insulated cables, in both cases with or without armouring. Further, when single-core V.I.R. cables are

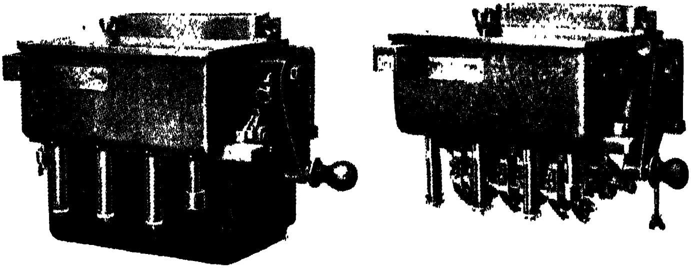


FIG. 3. TYPICAL CIRCUIT BREAKER FOR WALL MOUNTING

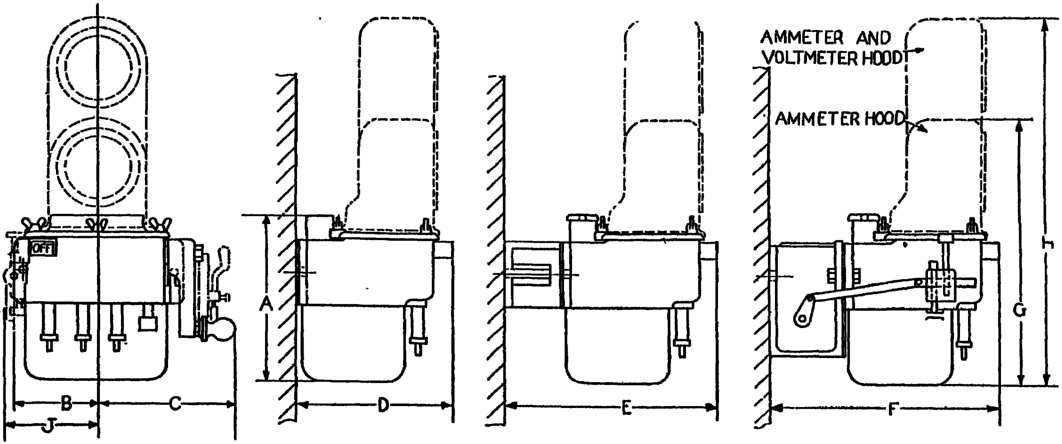
Suitable for six single-core V.I.R. cables entering through a wood bush. Complete with three A.C. over-current series trips and under-voltage release.

employed, bushes are fitted, or, alternatively, fittings for screwed conduit.

As shown in Fig. 1, an ammeter or a voltmeter may be fitted, or both, and the former may be scaled in horse power, if an efficiency curve of the motor is available for calibration of the scale.

For currents up to 120 amp. and for duty at 660 volts and below, a simpler and less expensive breaker of the type illustrated in Fig. 3 may be employed.

This breaker embodies similar features to those described for the oil circuit breaker illustrated in Fig. 1 and, having rope- or felt-packed joints, complies with the General Regulations as to the Installation and Use of Electricity in Mines and Quarries, Form II, Coal Mines Act, 1911, where flameproof enclosure is not required.



Front elevation (isolator shown chain dotted). Wall-mounted breaker only. With combined bracket and sealing box. With triple-pole isolator.

Size		A	B	C	D	E	F	G	H	I
(3–60 amps.)	in. mm.	$12\frac{1}{4}$ 312	$6\frac{1}{8}$ 156	10 254	$11\frac{1}{2}$ 292	$15\frac{3}{4}$ 400	$16\frac{3}{4}$ 426	$18\frac{3}{8}$ 467	$27\frac{1}{2}$ 699	$6\frac{5}{8}$ 169
(80–120 amps.)	in. mm.	13 330	$7\frac{5}{8}$ 194	$11\frac{1}{4}$ 286	$12\frac{1}{2}$ 318	$17\frac{1}{2}$ 445	$17\frac{3}{4}$ 451	19 483	27 686	$8\frac{3}{8}$ 213

FIG. 3A. APPROXIMATE DIMENSIONED OUTLINES

Wall-mounted Breakers

A breaker such as that illustrated in Fig. 3 is employed to control relatively small size motors or circuits, so that where it is desired to isolate the breaker, the cost of drawout features and pedestal mounting would not be economic. For this reason a metal-enclosed isolator is available on some types of this

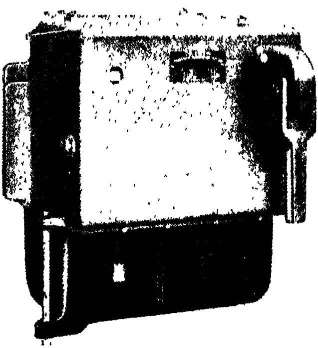


Fig. 4

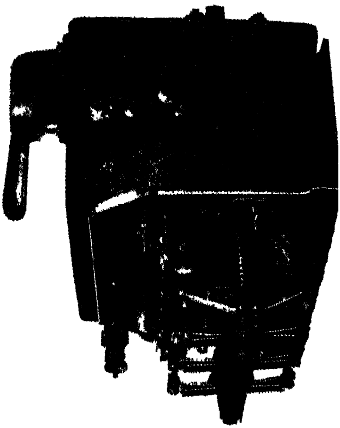


Fig. 4A

Typical Wall-mounted Oil Circuit Breaker

breaker which enables the breaker to be isolated from the line for cleaning or maintenance purposes.

The position of the isolator is shown in the dimensioned sketch (Fig. 3A), and when fitted is interlocked as follows—

(*a*) The isolator cannot be opened whilst the starter is in the " running " position, thus the circuit is always made and broken on the starter contacts.

(*b*) The cover and oil tank of the starter cannot be removed whilst the isolator is in the " on " position.

(*c*) The isolator cannot be closed whilst the cover and oil tank are removed.

Still another example of a wall-mounted oil circuit breaker is that illustrated by Fig. 4 which is rated at 200 amp. up to 660 volts.

The particular breaker shown is of special interest, in so far as the main contacts are concerned, in that the conventional wedge and spring-backed finger

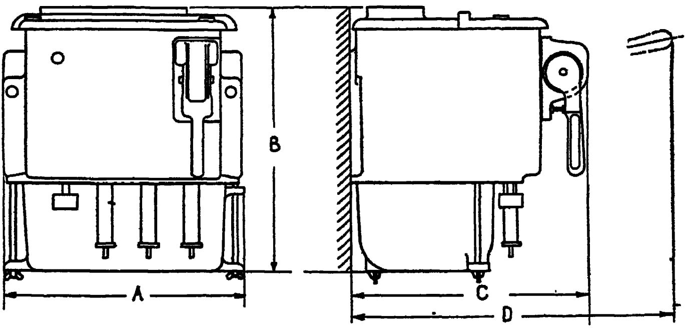


FIG. 4B. APPROXIMATE DIMENSIONED OUTLINE

A		B		C		D	
in.	mm.	in.	mm.	in.	mm.	in.	mm.
14	356	15	381	13¾	350	19	483

contacts are replaced by "Contactor" type contacts in which a high contact efficiency is obtained with powerful compression springs. Such an arrangement occupies a smaller space and is less expensive than the orthodox contacts.

For still smaller motors, say, up to 15 h.p. at 440 volts, an oil circuit breaker of the type illustrated in Fig. 5 has recently been introduced to the English market, although it has been widely used for some time on the continent of Europe.

Such a breaker has a maximum current rating of 30 amp. at 500 volts.

The novel features of this breaker are a thermal overload device combined with an instantaneous short-circuit trip. The breaker is virtually a contactor, in that the contacts are closed by a pot magnet, the circuit

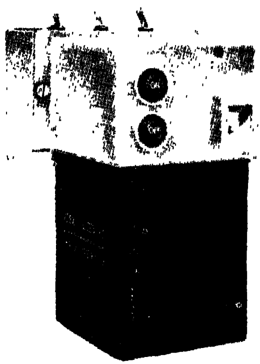


FIG. 5A. TYPICAL THERMAL CIRCUIT BREAKER

FIG. 5B. 30-AMP. BREAKER
Cover and oil tank removed

of which is made or broken by push buttons and maintained when the breaker is in the closed position by auxiliary contacts. These contacts, however, are broken by the thermal trip, the design of which is such that a bimetallic strip is heated by the circuit current, and when heated distorts sufficiently to open the auxiliary contacts, and thus trip the breaker.

An instantaneous trip is secured by a hinged armature which is moved electro-magnetically by a short-circuit current, the movement opening the auxiliary contacts in the same manner as the thermal trip.

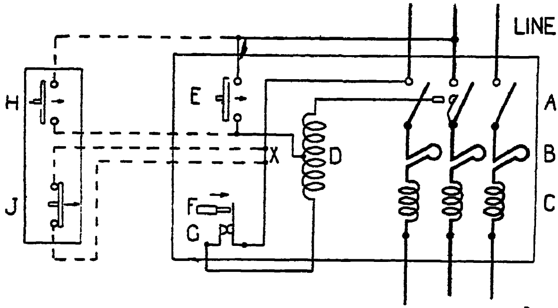


Fig. 5c. Connection Diagram for a Type JA1 Thermal Circuit Breaker

A—Main Contacts.
B—Thermo strips.
C—Instantaneous trip coils.
D—Energizing coil.
E—" On " Push-button.
F—" Off " push-button.
G—Auxiliary Switch (opens automatically by the action of either *B* or *C*).

Note.—" On " and " Off " push-buttons, *H* and *J* are additional for direct and remote hand control, and the connections from the breaker are shown dotted. When this arrangement is required there is no through connection at *X*.

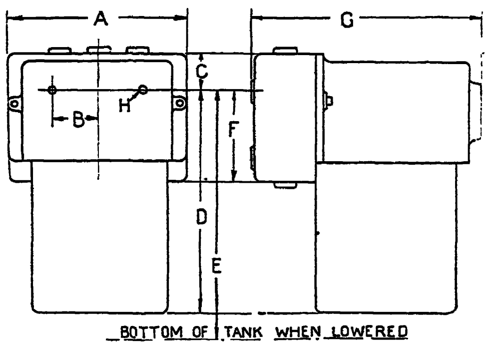


Fig. 5d. An Approximate Outline of a Thermal Circuit Breaker

For all Standard Current Ratings

	A	B	* C	D	E	F	G	H
in.	6	$1\frac{1}{2}$	$1\frac{13}{16}$	$6\frac{15}{16}$	$12\frac{7}{16}$	$2\frac{7}{16}$	$7\frac{5}{8}$	$\frac{1}{4}$ dia.
mm.	153	38	46	177	316	62	194	7

* When an ammeter is supplied, dimension " C " is 5 in. (127 mm.).

The breaker thus has a time lag overload release and an instantaneous short-circuit trip, so ensuring a motor is only disconnected when a dangerous temperature rise occurs in its windings or a short-circuit develops at its terminals or in the inter-connecting cables.

By reason of the electrical closing arrangement, this breaker can be remote electrically operated from a suitable push button switch. Such applications occur in connection with machine tools, printing presses, and industrial duty where it is advantageous to be able to control the electric drive at the work.

Electrical interlocking can also be simply arranged by auxiliary contacts on the motor starter working in conjunction with the closing coil, which incidentally was a mid-point tap for closing to obtain the initial effort necessary to start the closing motion.

STAR-DELTA BREAKERS

Small induction motors up to, say, 25 h.p. at 500 volts may be started direct from the line, the motor in this case having a squirrel cage rotor.

In order to limit the initial current rush on starting to a reasonable value, a special starting switch is employed whose contacts are so arranged that in the "starting" position the windings are connected in star and when the motor is up to speed the switch is changed to the "running" position which re-connects the winding in delta. With this scheme only 58 per cent normal volts are applied to the phase winding when starting, and, consequently, the starting current taken from the mains is limited to approximately $1\frac{1}{2}$ times full load, or about one-third of the current which would be taken if the motor were switched direct on to the line.

This method of starting requires the motor to have

both ends of the phase windings brought out to terminals on the frame, and necessitates six leads between the motor and the starting switch.

A switch of this type which is usually termed a Y-delta starter is illustrated in Fig. 6.

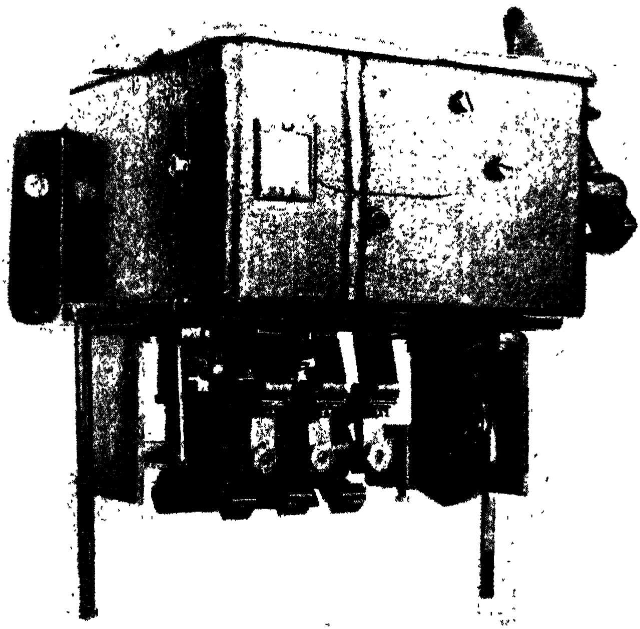


FIG. 6. TYPICAL Y-DELTA STARTER

It will be observed the moving contact comprises a spindle carrying star-shaped segments which bridge stationary contacts either side, and form the star-delta connection.

Such a switch is fitted with series overload release,

low-volt release with or without interlocks, either ammeter or voltmeter, or both, and when required a metal-enclosed isolator.

PEDESTAL-MOUNTED NON-DRAWOUT GEAR

The whole of the wall-mounted breakers referred to in the previous paragraphs may be mounted on a

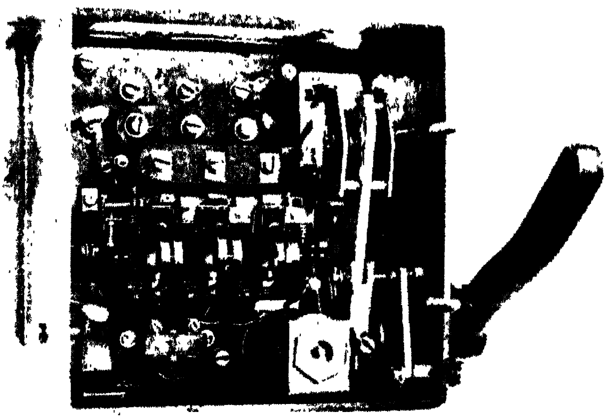


FIG. 6A. TYPICAL Y-DELTA STARTING SHOWING AUTOMATIC RELEASES

pedestal either for reasons of convenience or where it is necessary to place the breaker close to the motor and no wall is available.

Typical pedestal-mounted breakers are illustrated by Fig. 7.

In cases where a number of circuits are to be controlled and a switchboard is necessary, then a special pedestal may be employed, the base of which contains the busbars and isolators.

Fig. 8 illustrates a switchboard of the type built up of pedestal-mounted oil circuit breakers.

In other instances the oil circuit breaker pedestal is made use of to contain the rotor starter, Fig. 9 illustrating this arrangement.

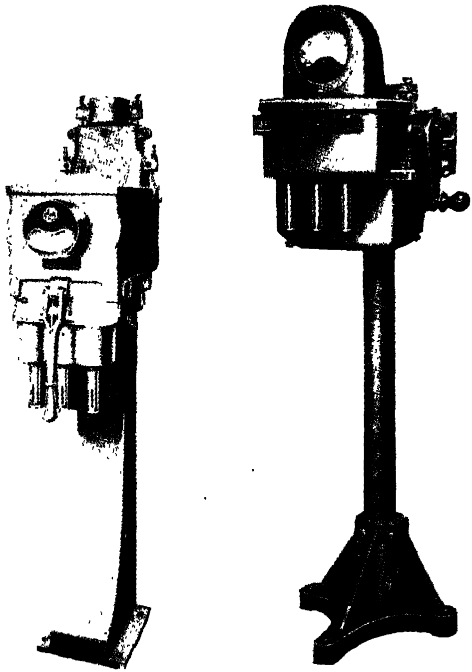


FIG. 7. TYPICAL PEDESTAL-MOUNTED BREAKERS

PEDESTAL-MOUNTED DRAWOUT SWITCHGEAR

This type of switchgear has a very wide application in that well-designed drawout gear can be fully interlocked and thus rendered foolproof, and, in addition, provides the maximum safety in operation and during

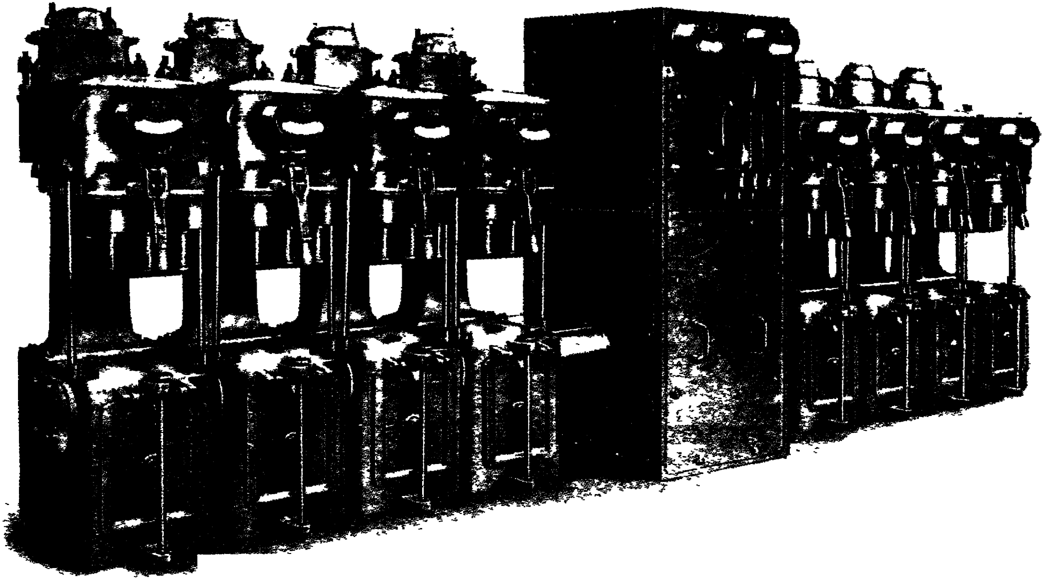
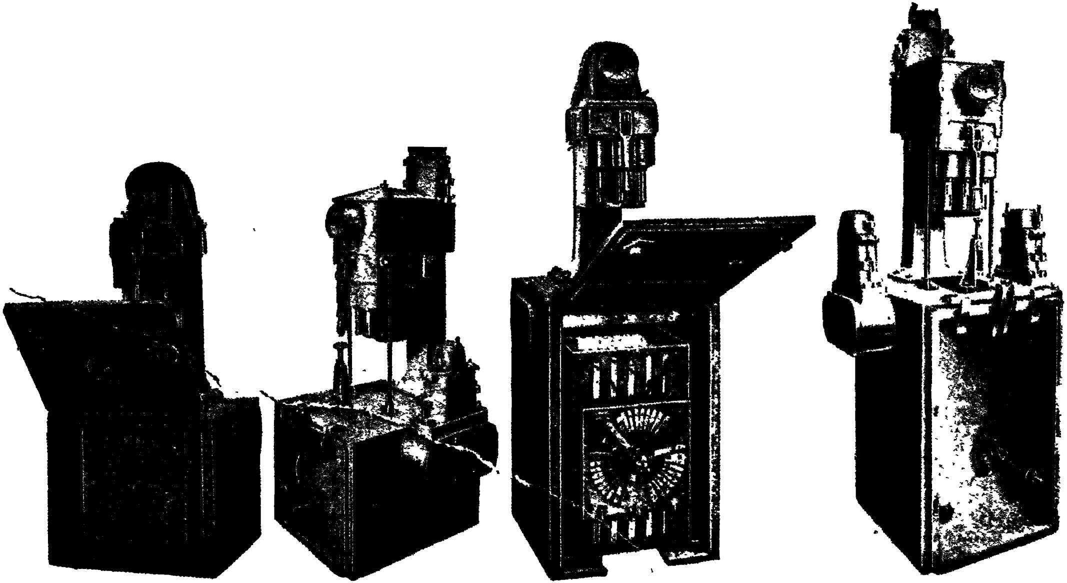


FIG. 8. IRONCLAD SWITCHBOARD



(Door open). (Door closed). (Door open). (Door closed).

FIG. 9. PEDESTAL CIRCUIT BREAKER

Containing starting rheostat for slip-ring induction motor.

maintenance, as the breaker can be entirely isolated from the busbars and circuit.

In the horizontal pattern of drawout gear the fixed portion comprises a pedestal supporting the busbar and circuit chambers, each of which are fitted with three insulated socket contacts. From the front of these chambers two slide rails project which guide the movement of the oil circuit breaker body. The moving portion comprises the breaker body which is provided with six plugging contacts engaging with the socket contacts on the fixed portion. The breaker is withdrawn and replaced manually, a screw arrangement being provided to lock the body in the engaged position.

When the breaker body is completely removed, the stationary contacts are protected by a hinged safety cover which may be locked in position.

Typical drawout pedestals are illustrated by Figs. 10 and 11.

Switchgear of this type embodies many interesting features in construction which are necessary in order that the gear shall be foolproof. For example, the following interlocks are fitted—

1. The breaker will automatically trip immediately if any attempt is made to withdraw it from, or replace it in, the service position.

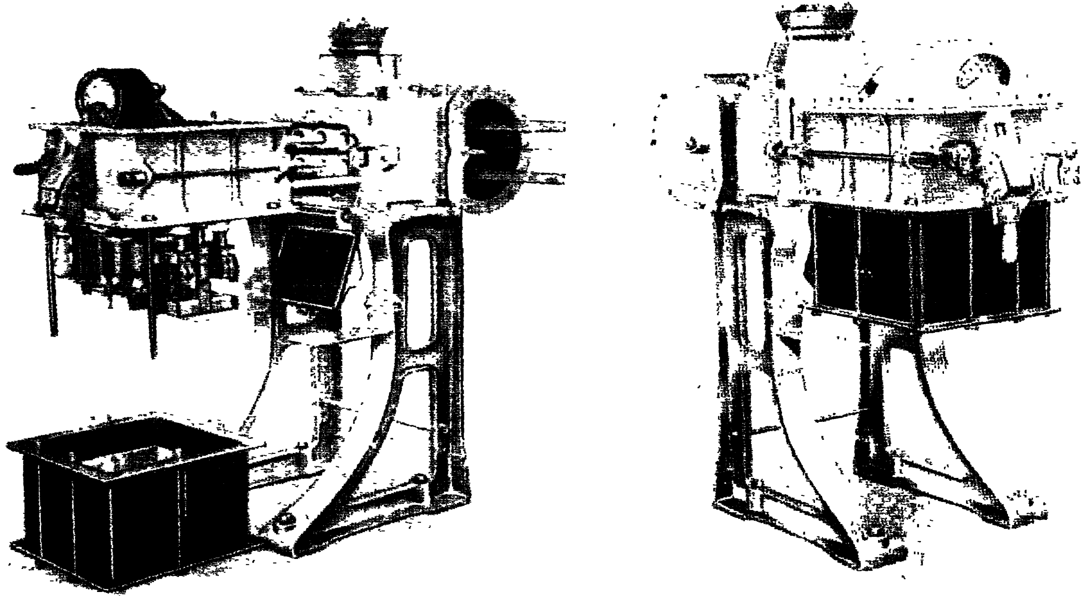
2. The breaker unit must be withdrawn to the isolated position before the oil tank can be removed.

3. The oil tank must be in position on the breaker frame before the breaker unit can be replaced in the service position.

4. The breaker can only be closed when it is in the service position, the isolated position, or the earthing position.

5. The cover can only be removed from the breaker unit when the latter is in the isolated position.

6. The cover must be in position on the breaker



In isolated position. In service position.

FIG. 10. 300 AMP. PEDESTAL-MOUNTED EQUIPMENT

unit before the latter can be replaced in the service position.

7. A definite stop is fitted to the breaker unit so that it cannot be inadvertently drawn off the slide bars.

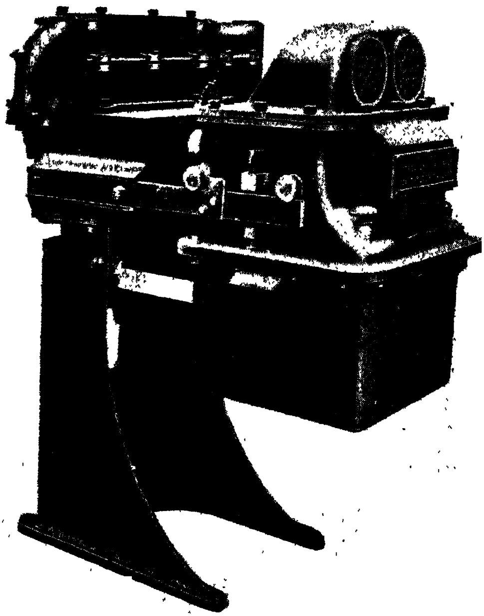


FIG. 11. TYPICAL PEDESTAL-MOUNTED DRAWOUT SWITCHGEAR

Most of these interlocks are obtained by suitable gates or slots on the slide rails in conjunction with combinations of links and levers, which either trip the breaker or prevent it being closed in accordance with the condition to be met.

An important feature in the design of drawout gear is the construction of the plug and socket contacts. Such contacts must be of a self-aligning type capable of maintaining good contact under adverse service and maintenance conditions.

A recent type of contact which has proved very satisfactory in service is the " hair-pin " type of socket

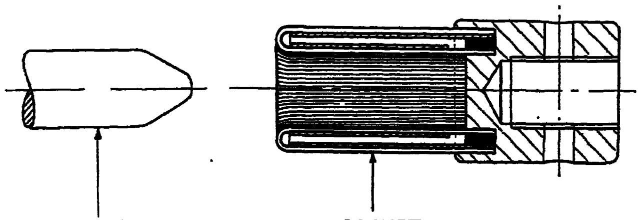


FIG. 12. 600 AMP. " HAIR-PIN " TYPE PLUGGING CONTACT

contact covered by British Patent No. /29007/1928. This is illustrated by Fig. 12.

In essence it consists of an annular carrier over which a large number of phosphor bronze " hair pins " are threaded longitudinally, and sweated into a groove at the head of the carrier. A resilient packing is fitted beneath the inner layer of wires, so that the latter may bed with an even pressure on the plug contact. Self-alignment is obtained by means of a flexible mounting for the plug, the construction being such as to allow $\frac{1}{8}$ in. to $\frac{3}{16}$ in. out of alignment according to the diameter of the plug.

Another successful modern design is shown on the next page in Fig. 13.

The socket contact in this case consists of a garter spring wound from suitable gauge phosphor bronze wire, the arrangement being such that when a plug is inserted the diameter of the contact is slightly

increased, and the spring tension thus developed exerts a pressure on the plug.

The secret of both these designs is that of a large number of line contacts under pressure, which experience in all lines of switchgear has shown, will give the most satisfactory and reliable contact.

Pedestal-mounted equipments of the type under review may be mounted together and fitted with busbars to form a switchboard. Fig. 14 illustrates a

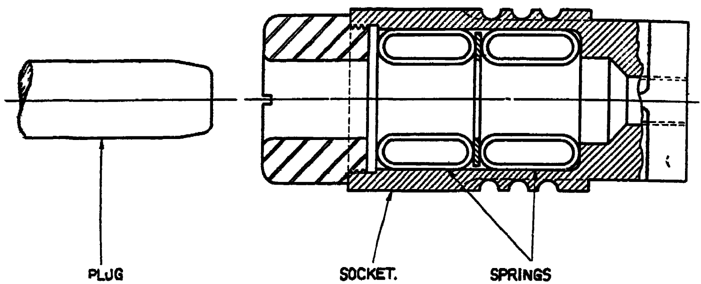


FIG. 13. 600 AMP. "GARTER SPRING" PLUGGING CONTACT

typical board consisting of one or more incoming feeders and a number of outgoing feeders.

Such switchboards, if desired, may be fitted with instrument equipment comprising intergrating watt-meters, power factor indicators, and busbar voltmeter, the meters being mounted on sheet iron panels above the oil circuit breaker.

A typical board is illustrated later, by Fig. 15.

The joints on this type of switchgear are rope, packed in conformity with the regulations, in order that the gear shall be suitable for all classes of industrial service and for use in non-fiery mines.

Where the gear is for colliery duty the Coal Mines Regulations Act stipulate that the circuit must be earthed through the oil circuit breaker before any work

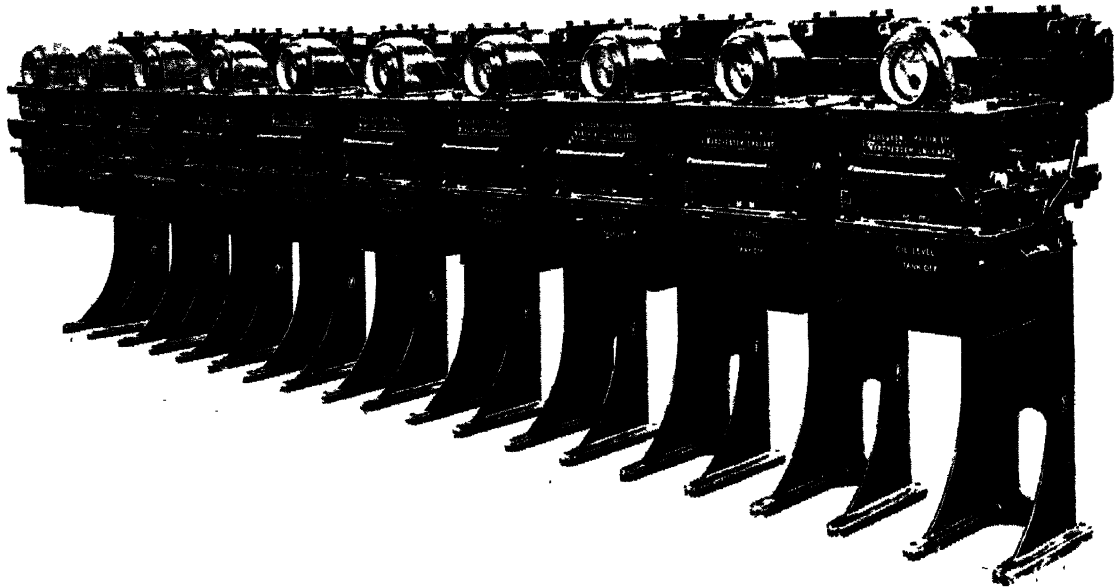


FIG. 14. TYPICAL IRONCLAD DRAWOUT SWITCHBOARD

is commenced. Two forms of cable earthing device are commonly employed.

(*a*) A permanent attachment mounted on the front of the cable circuit chamber.

(*b*) A self-contained detachable device.

The *permanent attachment* is illustrated by Fig. 16.

This attachment consists essentially of a rectangular cast housing within which a horizontal metal bar carrying three spring contact receptacles, and connected to an external bridge piece, is arranged to slide up and down. The housing itself is connected to earth by heavy copper strips. The "cable" side of the circuit breaker is provided with contact plugs slightly longer than those on the "busbar" side.

When the earthing device is not in use the metal bar is held clear of the isolating contact plugs, the latter passing through apertures in the housing for normal engagement with the receptacles.

When it is desired to earth the cable, the breaker unit is withdrawn and the bridge is moved to bring the spring receptacles into line with the shorter contact plugs. The breaker is then pushed into the earthing position where it can be locked. In this position the longer contact plugs engage with the receptacles on the "cable" side of the equipment in the usual manner, but the shorter plugs engage with the spring receptacles in the earthing device.

The breaker is then closed and padlocked, thus completing the circuit between the cable and earth.

The *self-contained earthing device* comprises three earthing receptacles and three insulated extension contact plugs, all separately mounted on a metal frame which is earthed through a contact plug and receptacle. When it is desired to earth the cable, this frame is inserted in between the breaker unit and the combined cable and connection chamber, the extension

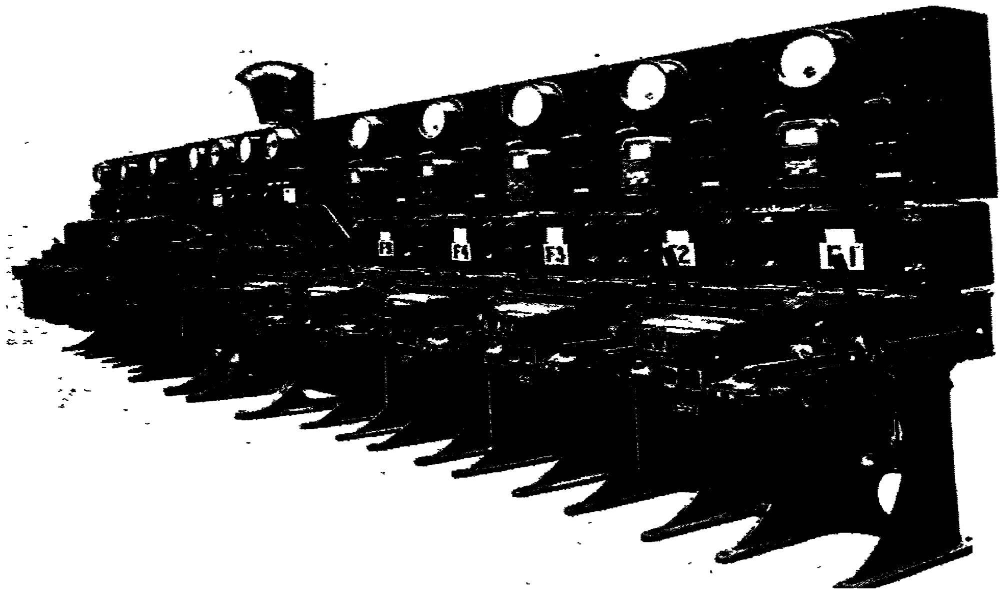


FIG. 15. IRONCLAD DRAWOUT SWITCHGEAR WITH INSTRUMENT PANELS

plugs being fitted over the ends of the breaker contact plugs to the " cable " side. The other breaker contact plugs fit into the earthing receptacles. The breaker unit is then pushed into the earthing position where

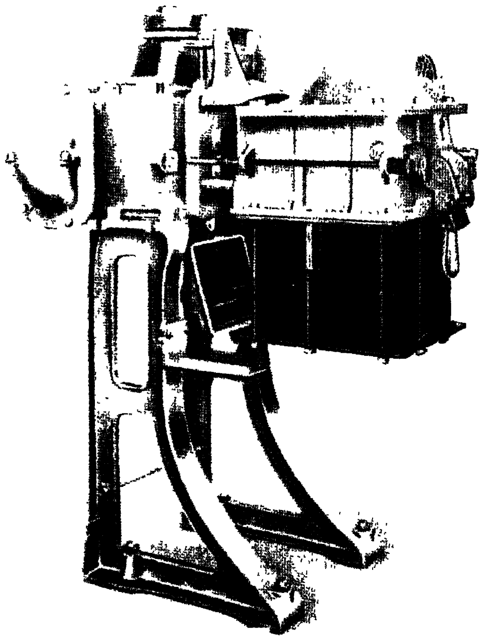


FIG. 16A. PEDESTAL EQUIPMENT, WITH CABLE EARTHING DEVICE PERMANENTLY ATTACHED
The breaker unit is shown in the earthing position.

it can be locked and the extension plugs engage with the contact receptacles on the " cable " side of the equipment. By closing the breaker the earthing circuit is completed.

The automatic features on the circuit breaker can

be arranged so that they are rendered temporarily inoperative while either form of earthing device is in use.

It is understood that the Department of Mines have expressed a preference for the permanent attachment

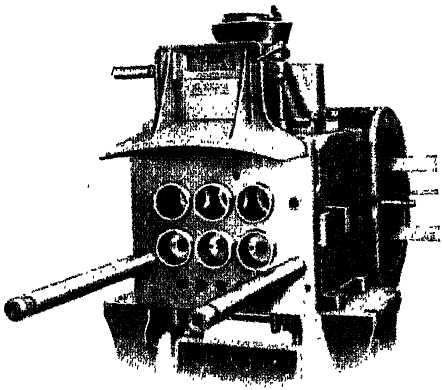


FIG. 16B. BREAKER UNIT REMOVED
To show a cable earthing device permanently attached to a typical equipment.

in that this affords greater encouragement to its use than the detachable arrangement.

FLAMEPROOF DRAWOUT SWITCHGEAR

When switchgear is for use in places where an explosive atmosphere may be encountered, such as a fiery mine, then flameproof switchgear must be employed.

On account of the importance of such gear British Standard Specification 229, 1926, has been prepared to cover the requirements.

This sets out the tests to which such gear must be subject in order to obtain a type test certificate which

must be secured before the switchgear will be passed for service by the colliery inspectors.

Investigation has shown that the maximum internal pressure which can be developed in a metal enclosure, due either to firedamp or oil vapour, is round about 110 lb. per square inch. The metal enclosures of all flameproof switchgear must, therefore, be designed to withstand this pressure without either leakage or damage.

To meet this condition it is customary to employ machined flange joints between the various components, and, in addition, the plug and socket contacts are fitted with long close-fitting sleeves to form flameproof enclosures during separation of the contacts, thus avoiding open sparking due to static effects.

As a further precaution, the busbar circuit and cable chambers on this class of gear are compound filled, so that the only unfilled chamber is in the head of the breaker.

Switchgear of this type is illustrated in Fig. 10 referred to previously.

LEAKAGE CURRENT TRIP

The Home Office General Regulations as to the installation and use of electricity in coal mines state in Regulation 128 (c) that "efficient means, suitably placed, shall be provided in respect of each separate circuit for cutting off all pressure automatically from the circuit or part or parts of the circuit affected in the event of a fault as may be necessary to prevent danger."

The explanatory memorandum relating to the above-mentioned regulations says that "while the installation of leakage protective devices is not insisted upon, the adoption of such additional protection is considered

desirable and is strongly recommended for serious consideration."

For circuits of small capacity, it is probable that sufficient protection will be obtained generally from circuit breakers fitted with three overload coils, but for all circuits of medium or large capacity, special leakage protection should be installed.

In all cases the object in view is to supplement the customary time limit overload protection by an additional arrangement to cause the circuit breaker to open directly leakage occurs, and without waiting for the leakage current to grow to any magnitude.

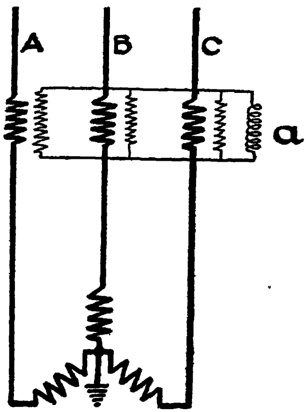


FIG. 17. DIAGRAM OF LEAKAGE TRIP

A standard leakage current device, as commonly supplied for use on earthed systems, is based on the fact that under normal conditions the sum of the currents in a three-phase cable equals zero. Therefore, with three similar series transformers connected one in each line as in Fig. 17, and having secondary windings connected to a common coil "A," no current will flow under normal conditions through the coil. If, however, a fault causes one phase to break down and leak to earth the balance becomes disturbed, causing out-of-balance current which is utilized to trip the circuit breaker.

In general, the apparatus supplied consists of three series transformers together with a relay, as illustrated in Fig. 18 which can be adjusted so that an out-of-balance current equal to from 5 to 10 per cent of the

rated full load current will open the circuit breaker. The relay has circuit opening contacts which break the current of the low-volt attachment. The relay is sometimes replaced by a special trip coil that is placed in one of the three overload coil positions. This requires for its operation not less than 40 per cent out-of-balance in the primary circuits.

A special core-balancing form of ring transformer may be employed instead of three separate transformers

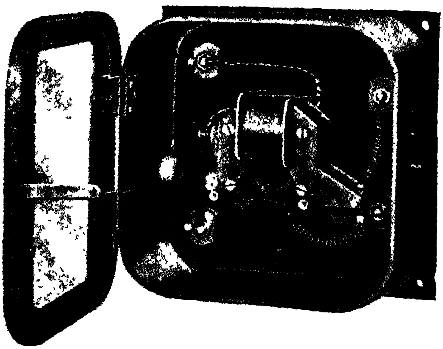


FIG. 18. RELAY

for use in conjunction with a relay, Fig. 18 above. This arrangement operates with a primary leakage current of approximately 15 amps.

It should be noted that the leakage protective arrangements described above refer only to circuit breakers for use on systems having the neutral point earthed, and that while the leakage trip is operated by any leakage current to earth, it will not be affected by any leakage that may occur between phases, although, should a short circuit take place between phases, the circuit breaker would be opened instantly by the overload coils.

VERTICAL PLUGGING DROP-DOWN SWITCHGEAR

The electrical auxiliaries in a power station, such as circulating water pumps, air pumps, induced draught fans, stoker motors, etc., all constitute important circuits. Switchgear to control these circuits is usually mounted in or near the engine room, and sometimes in the basement, either position making it desirable to

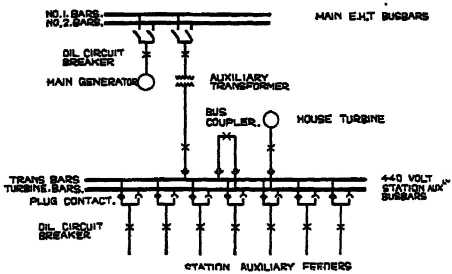


FIG. 19. KEY DIAGRAM OF POWER STATION AUXILIARY CIRCUITS

use an enclosed form of switchgear. Space considerations also render ironclad gear preferable, as this type occupies less room than equivalent panel-type gear.

In many modern power stations the auxiliary supply is derived from two alternative sources, first a house turbine, that is an independent turbine-driven alternating current generator, and, secondly, an auxiliary transformer, connected to the main E.H.T. busbars.

The operating arrangements vary in different stations, but whether the power units operate in parallel or independently, the conditions require that the switchgear shall have duplicate busbars. These would be connected as shown on the key diagram (Fig. 19).

The aggregate capacity of the station auxiliaries may be considered as 5 per cent of the plant capacity

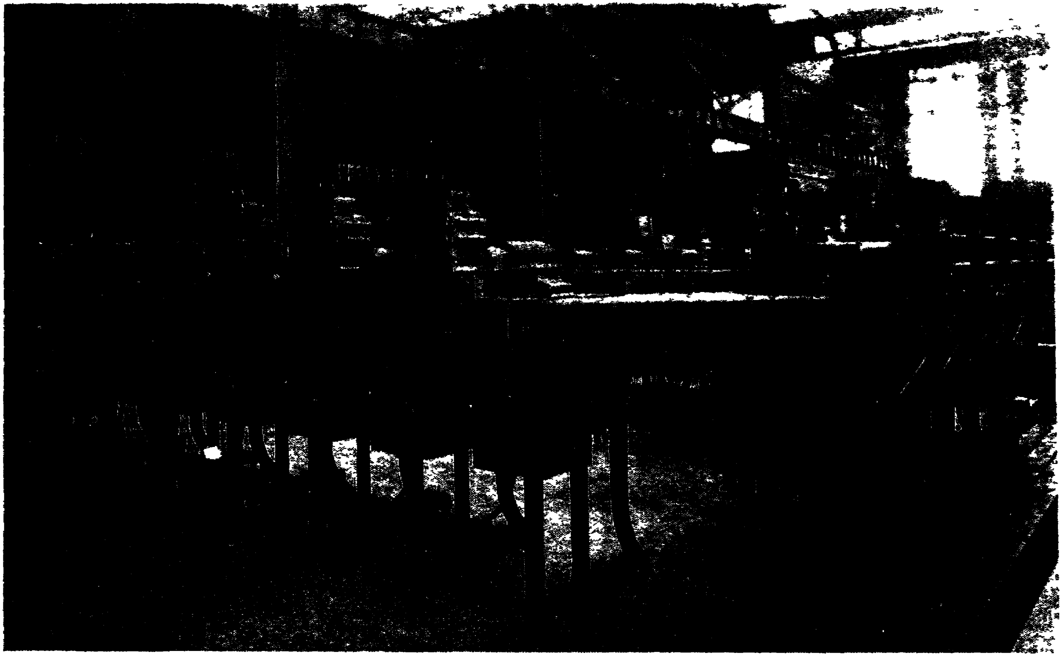


Fig. 20. Vertical Plugging Duplicate Busbar Ironclad Switchgear

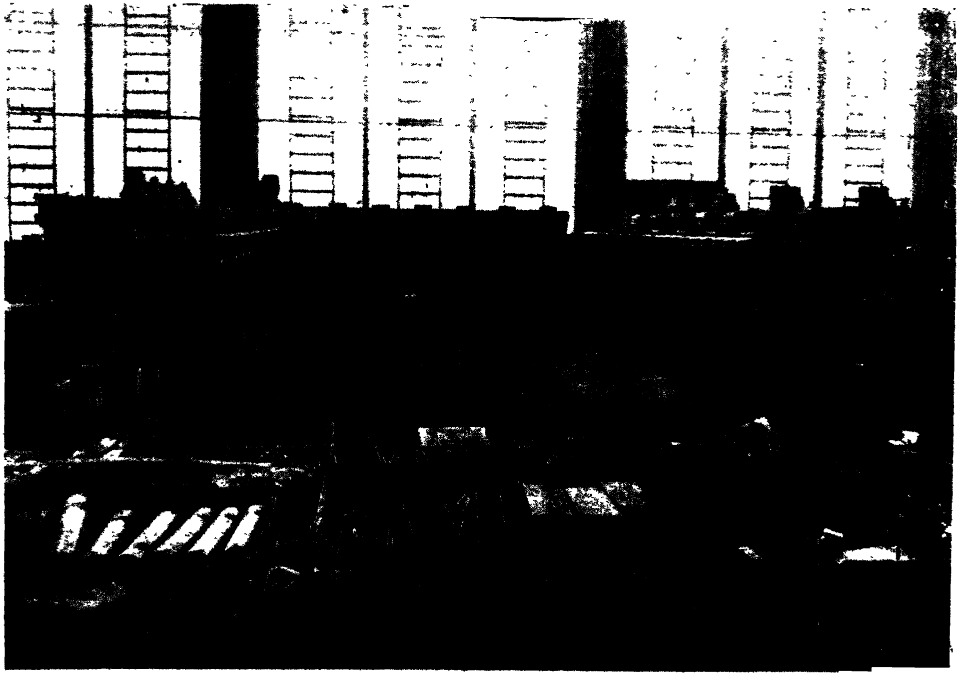


FIG. 21. VERTICAL PLUGGING IRONCLAD SWITCHGEAR

which means that in the larger power stations the house generator and auxiliary transformer may be 3000 kVA capacity, which at 440 volts corresponds to a current rating of 4000 amp.

To meet all the conditions obtaining, namely, an ironclad-enclosed type of gear with duplicate busbars for controlling heavy currents, a Vertical Plugging drop-down arrangement of gear has been found to work out most satisfactorily.

Typical equipments are illustrated in Figs. 20, 21, and 22.

In essence this gear consists of vertical side frames carrying the busbar and circuit chambers, fitted with socket contacts which engage with plug contacts on the top of the oil circuit breaker.

Busbar selection is obtained by the position of the breaker which is dropped, traversed, and then raised when it is desired to change a circuit from one bus to the other. Movement of the oil circuit breaker is carried out by a carriage fitted with screw lifting gear, the breaker being held in the engaged position by movable stops or blocks.

The vertical motion of the breaker is guided by spears on the breaker top which engage with guides on the stationary portion, and so ensure the plugs and sockets are properly aligned when they enter.

When the breaker has been isolated by lowering, the socket contacts on the stationary portion are covered by hinged eyelids so that no live parts are accessible.

On equipments above 800 amp. rating, the chambers have to be constructed of non-magnetic iron or, alternatively, an insert of non-magnetic material welded into the wall of the chamber at one or more points in order to break the magnetic circuit.

For heavy currents the plug and socket contacts consist of laminated blades engaging with spring clips,

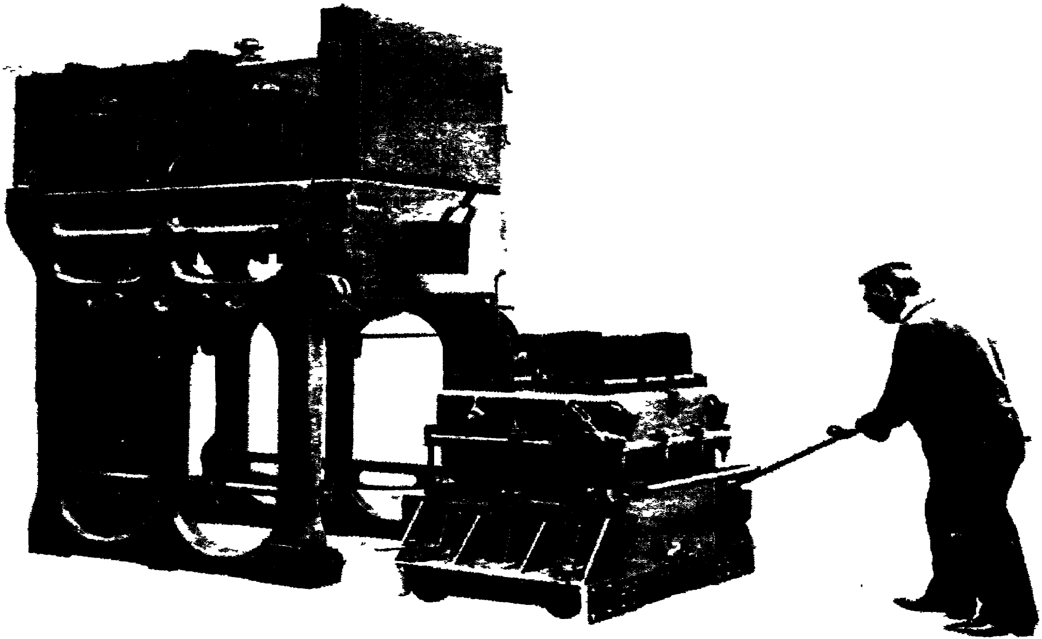
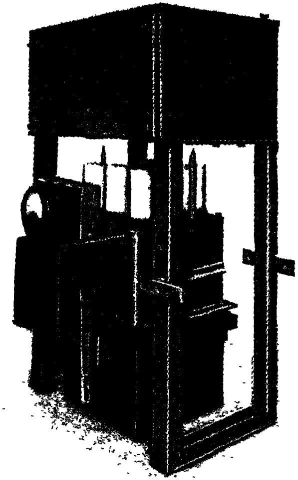
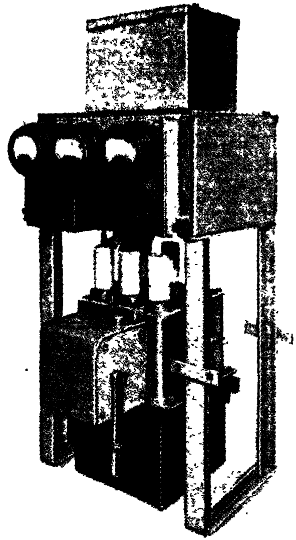


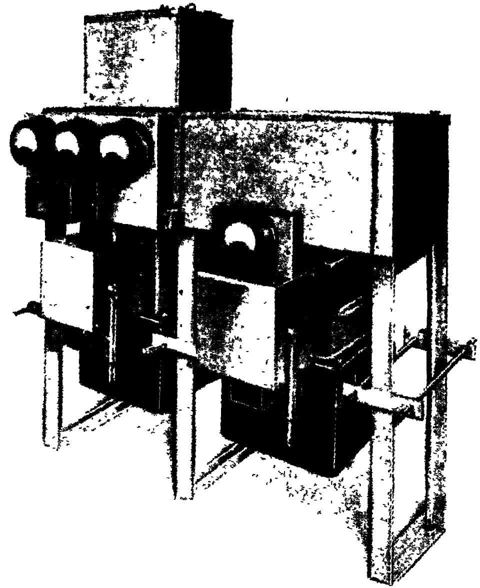
FIG. 22. TYPICAL HEAVY CURRENT VERTICAL PLUGGING SWITCHGEAR



Typical simple equipment with ammeter on breaker

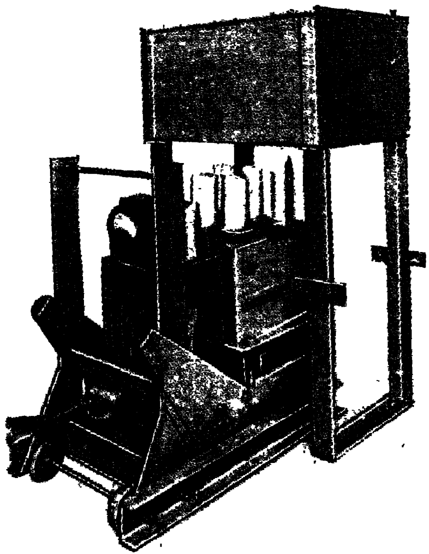


Typical equipment with instrument panel on the fixed unit and voltage transformer on top

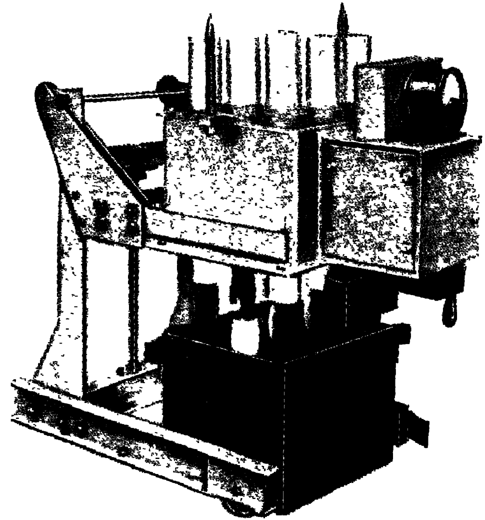


Typical switchboard of two equipments.

FIG. 23. VERTICAL PLUGGING IRONCLAD SWITCHGEAR



Withdrawal Carriage showing screw mechanism for raising the movable unit into service position.



Withdrawal carriage showing movable unit completely withdrawn and raised so that breaker contacts can be readily inspected.

FIG. 24. VERTICAL PLUGGING IRONCLAD SWITCHGEAR

a sufficient number being employed in parallel to carry the current.

The circuit and busbar chambers may be filled with compound if desired, but on heavy current circuits up to 650 volts it is preferable to omit filling in order to permit free radiation of heat generated in the conductors and at joints. Alternatively, if filling is adopted then very low current densities in the order of 250/400 amp. per square inch must be used, which renders the gear inordinately expensive.

By reason of the saving in space and economies in cost which can be effected with the drop-down arrangement of ironclad switchgear, this pattern is now becoming popular for industrial service. A modern design recently introduced is illustrated in Figs. 23 and 24.

Such gear is constructed throughout of welded material, castings being entirely eliminated. The general arrangement does not differ greatly from the duplicate busbar gear previously described, except that the busbar and circuit chambers are designed for oil filling when air insulation is not considered sufficient. Gear of this type can be readily made suitable for outdoor duty, since the stationary portion forms an umbrella for the breaker, and the plugging contacts.

The foregoing describes the types of ironclad switchgear in most general use. Other patterns of ironclad switchgear have similar applications, including truck switchgear and compound-filled switchgear, and for certain classes of duty ironclad switch fuse boards are employed. These alternative types of switchgear are, however, covered by other sections of this publication.

Acknowledgment is given of the courtesy of the British Thomson-Houston Company, The Metropolitan-Vickers Company, and Messrs. Ferguson, Pailin, Ltd., for information and illustrations supplied in the preparation of the foregoing.

SECTION XV

PROTECTIVE SYSTEMS FOR A.C. MAINS

BY

BRUCE HAMER LEESON, A.M.I.E.E.

SECTION XV

PROTECTIVE SYSTEMS FOR A.C. MAINS

GENERAL PRINCIPLES AND CLASSIFICATION

THE primary objects of protective systems for alternating current electric mains are to isolate automatically and immediately any main which develops a fault, to limit the extent of the damage produced by a fault, and to secure what is commonly called *continuity of supply*. The latter, which is of vital importance, may be defined as the maintenance of a continuous supply of electricity from an electrical undertaking to its consumers under all conditions of service.

The failure of a supply of electricity to an industrial consumer may interfere seriously with a manufacturing process and result in the manufactures being flawed or rendered useless, quite apart from the loss of output incurred during the time the supply is interrupted.

A failure is equally serious in the case of public places and utility buildings, of vital importance in the case of hospitals, and of intimate concern to every domestic consumer. Thus, a failure of supply may involve an electrical undertaking in direct monetary loss through compensation claims, apart from the loss in revenue, and in every case it incurs loss of prestige and confidence, with consequent retardation of further business. The damage done to plant and mains by a short-circuit fault current and the subsequent cost of repairs or renewals are each reduced to a minimum by the use of discriminating protective systems which automatically open the circuit breakers controlling the faulty

plant or main and isolate it immediately, before much harm or damage can be done.

Protective systems form an integral part of switchgear, and the need for both of them and their combined behaviour in an electrical distributing system (consisting of plant and network) may be likened to the need and behaviour of the brain, muscular, and nervous systems in an animate body because, in each case, discrimination, control, and action are exercised in a manner which is most suitable for efficient performance, and self-preservation from harm or damage.

Experience has proved that the capital charges for protective systems are more than repaid by the money they save by reduced cost of renewals and repairs and continuity of supply under fault conditions, and the larger and more important the electrical undertaking becomes, the more this applies.

Protective systems are required for various types of electric mains, such as single feeders, trunk feeders, independent or radial feeders, interconnectors, and ring mains.

The conditions of service to be met by protective systems are consequently many and various. This has resulted in a number of protective systems being developed to meet some particular case or condition to the best advantage, and hence many are only applicable to one particular type of main or limited conditions of service. One of the principal merits upon which to judge a protective system is its ability to be applied universally to all types of electric mains under any conditions of service, and this merit is possessed by certain modern protective systems.

The majority of the protective systems described in this section are applicable primarily to high and extra high voltage three-phase distribution systems of 3/3·3 kV to 200/220 kV, and form integral portions of

the switchgear described in Sections IX, X, and XI. Protective devices primarily applicable to low and medium voltage systems, such as a 440 volts distributing system, have been excluded.

An attempt has been made in this section to classify the principal protective systems which are available for the duty outlined, to present the relative qualifications and merits of each class, and to describe the principles upon which they function. Selected examples of typical protective systems are given, but only those which have been tried out under practical working conditions of service have been described.

The subject has been treated primarily from the point of view of engineers responsible for continuity of supply, and this includes as one of the most important items that a protective system shall infallibly isolate a faulty main, but never a healthy one. Throughout the section, therefore, constant reference has been made to what the author calls a *stability factor** and a *stability diagram*, and it is hoped the prominence given to these, coupled with the further aid of the more usual illustrations and description, will enable the reader to gain easily a knowledge of protective systems for alternating current mains.

Duty and Terms. The manner in which protective systems for electric mains are required to function may be obtained from Fig. 1 which illustrates a simple interconnected network fed from a power station.

When a fault occurs on the protected main *DE*, switches *D* and *E* only are required to open automatically and isolate it, whilst switches *A*, *B*, *C*, *F*, and *G* are required to remain closed and maintain continuity of supply to all stations. This is called *discriminating protection*. In practice it is found to be unnecessary to provide the switchgear in each station

* *I.E.E. Journal*, 1925, Vol. 63, p. 1025.

with a separate protective system, although busbars are occasionally protected in this way. The general practice, however, which is shown in Fig. 1, is to provide a secondary protective system at the power station which takes a longer time to function than those protecting the mains, so that should any unprotected unit, such as a busbar, develop a fault, or the

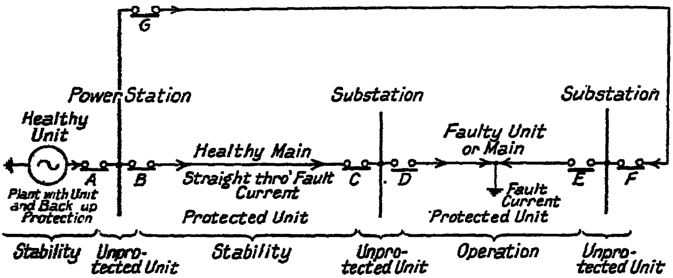


FIG. 1. PRINCIPLE OF DISCRIMINATING AND BACK-UP PROTECTION

protective system of any main fail to operate from any cause, the fault is isolated automatically by the secondary protective system opening the switches at the power station. This is called *back-up protection,* and for the network illustrated entails a complete shut down.

With this brief explanation of the duty of protective systems and the aid of Figs. 1 and 4, it will be helpful to consider the meaning intended to be conveyed by some of the more important terms used in this book for which definitions may not be found in the usual technical dictionaries.

When reading the definitions given below, it should be remembered that their meaning will become clearer by the explanatory matter which accompanies their use in the pages which follow.

The primary duty of a modern protective system is

that it shall discriminate between a healthy and a faulty condition in the main or unit it protects and function accordingly. This is called *Discrimination* and entails two essential characteristics. The first is called *operation*, which denotes the ability of a protective system to isolate the protected unit when it is *faulty*. The second is called *stability*, which denotes the ability of a protective system to remain inoperative when the unit it protects is *healthy*, but carries the maximum short-circuit current which can flow into another faulty unit beyond it. This fault current is called the *straight-through current*.

The primary fault current required to cause operation of a protective system is called the *fault setting*. The secondary current required to flow through a protective relay to cause operation is called the *relay setting*. The time taken by the relay to operate is called the *time setting*.

The operation of a protective system (having no stability) from any undesired cause, such as a straight-through current, is called *inadvertent operation*.

The *setting for operation* of a protective system is the value of the fault or relay setting required to produce operation.

The *setting encroachment* is a value, expressed in terms of the fault or relay setting, which represents the tendency to inadvertent operation produced by imperfections in the protective system.

The *stability factor* of a protective system is a measure of the margin of safety provided for stability and equals the ratio between the setting for operation and the setting encroachment.

A protective system whose stability is independent of protective systems or faults on other units, and whose operation only extends over the unit it protects, is said to provide *unit protection*.

A protective system whose stability is dependent upon the operation of protective systems of other units, and whose operation extends over a range of protected or unprotected units, is said to provide *back-up protection*.

Discrimination. The problem of providing a protective system with discrimination so that correct stability and operation are secured, is one upon which much thought and ingenuity has been displayed. All the various methods employed in practical protective systems to secure discrimination fall within the scope of the following three general principles.

The first is *time grading*, whereby operation of the protective system of the faulty unit occurs first, and the operation of the protective systems of the healthy units is prevented by a time interval for stability.

The second is *differential balance*, whereby the protective systems of the healthy units possess stability by remaining balanced, and operation of the protective system of the faulty unit occurs by its becoming unbalanced.

The third is *insulation breakdown*, whereby the protective systems of the healthy units possess inherent stability, and operation of the protective system of the faulty unit is performed directly by the fault current.

Operation. The fault settings which are required to produce operation of protective systems do not necessarily remain constant because in many cases they are governed by the value of current in the faulty unit. For example, differentially-balanced protective systems have three characteristic types of fault setting, namely, constant, variable, and graded, as shown in Fig. 2. In some systems the fault setting depends upon the load current or the location of the fault, or both.

The stress imposed upon plant and network, and the extent of damage done to them by a given fault current,

depends upon the time it is allowed to persist, and for this reason the operation of a protective system should be as nearly instantaneous as possible. The time taken by time-graded protective systems to produce operation and hence isolation of a fault, is one of their chief disabilities.

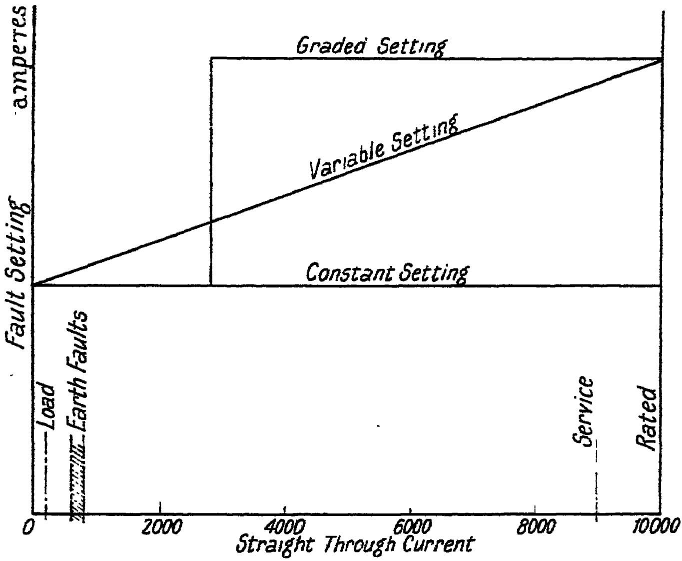


FIG. 2. TYPES OF FAULT SETTING

Fig. 3 illustrates how the fault setting of a protective system has an inappreciable effect upon the stress caused by a fault current, because it has no influence in preventing the current rising instantaneously to its maximum value. So long as the earth fault setting is well below the permitted earth fault current (assuming a resistance-earthed network as shown in Fig. 3) and the phase fault setting is reasonable, there is no particular merit in what are often called low fault settings,

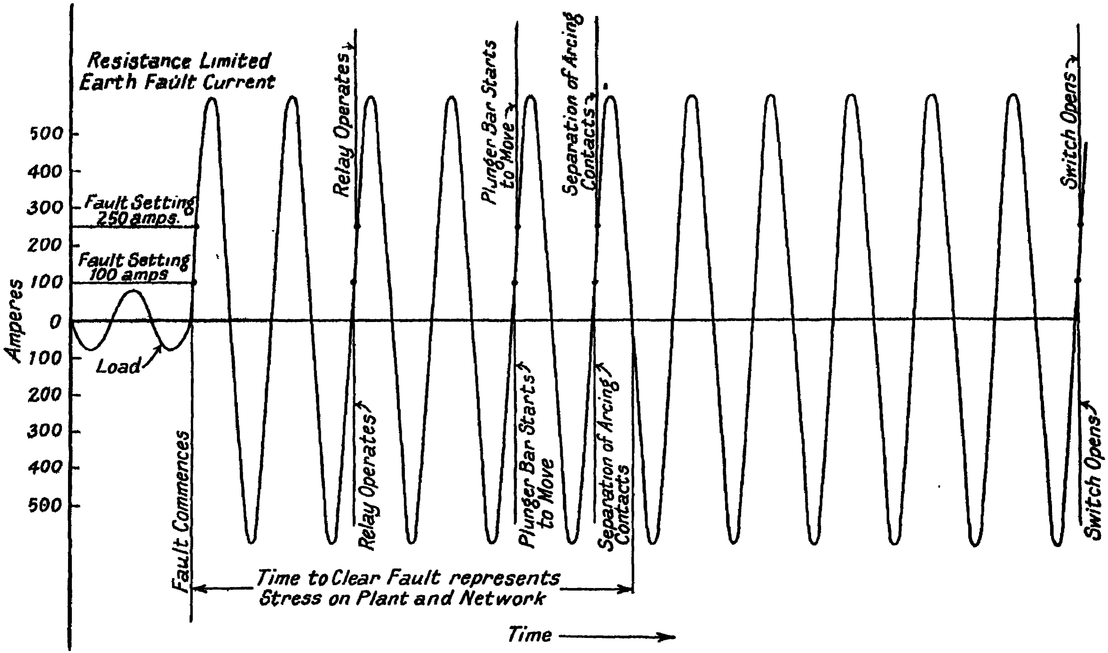


FIG. 3. DIAGRAM ILLUSTRATING STRESS ON PLANT AND NETWORK FOR EARTH FAULTS

which are generally obtained at the expense of stability and are far too high in value to possess the advantage of being able to cause operation by incipient fault currents.

Stability.* Clothier has emphasized that the criterion of quality of a protective system is its stability. This quality is most conveniently expressed by a *stability diagram* as shown in Fig. 4, and rated by a *stability factor*. In Fig. 4 the relay "setting for operation" is indicated by AS and the relay "setting encroachment" by BE, which represents the tendency for inadvertent operation to take place owing to imperfections in the protective system. The stability zone represents the margin of safety by which the setting for operation exceeds the setting encroachment. The stability factor is the ratio between these two factors on any ordinate. Thus, taking the ordinate OES in Fig. 4 the

$$\text{Stability factor} = \frac{\text{setting for operation}}{\text{setting encroachment}} = \frac{OS}{OE} = 2$$

It will be apparent that the criterion of the stability of a protective system is the minimum value of the stability factor, and in Fig. 4 this happens to occur at the maximum value of the quantity governing "setting for operation" and "setting encroachment," but in another diagram it might occur at some other value.

The entire success or otherwise of a protective system depends upon the correct calculation, or test measurement, of the disturbances tending to produce inadvertent operation by encroachment upon the relay setting. It is lack of knowledge, and insufficient study of the somewhat complex conditions which are set up in a protective system of a healthy unit when a fault occurs

* *I.E.E. Journal,* Vol. 63, 1925, pages 438 and 1033.

in another unit, that have led certain systems to fail in service through lack of stability. Thus, should any factor tending to produce inadvertent operation be present in actual service which has not been foreseen and allowed for in the design or experimental stage of the development of a protective system, the stability

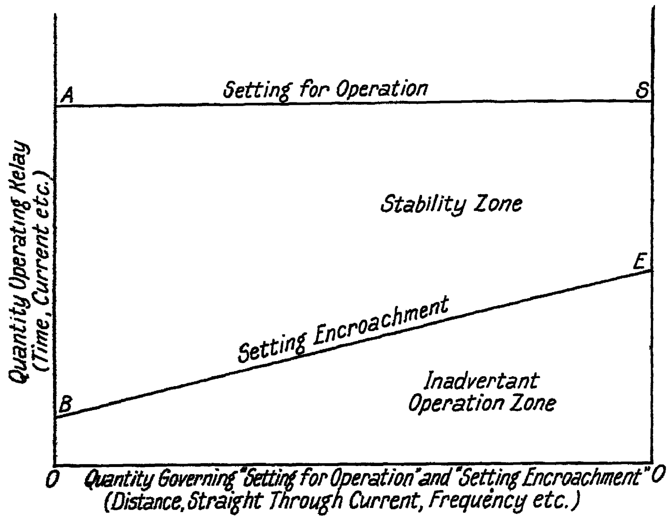


FIG. 4. FUNDAMENTAL STABILITY DIAGRAM FOR DISCRIMINATING PROTECTIVE SYSTEMS

zone will be encroached upon and inadvertent operation may result. It is of paramount importance that the stability diagram and stability factor of a protective system should be determined by tests which are fully representative of actual service conditions.

Protective systems might be classified under the three principles by which discrimination can be obtained, but this would be rather too broad to be useful. The protective systems in this section have, therefore,

been classified by the nature of their stability diagram in addition to the method by which they obtain discrimination, because this gives a better practical classification and enables the underlying principles to be understood more easily. In this way the protective systems have been divided into the following classes which form the titles of subsequent headings.

Classification	*Discrimination*
"Time-graded" class.	Time grading
"Distance" class	Time grading by distance
"Special Mains" class	Insulation breakdown Differential balance
"Feeder arrangement" class	Differential balance
"Merz-Price" class	Differential balance with pilots

The protective systems described and illustrated in the following pages represent examples of modern practice which have been installed on three-phase networks, and tried out under service conditions. Wherever known to the author, the name of the inventor is given in a footnote, unless it already appears in the title of the system or device associated with it.

Rating. The rating of a protective system should specify all the qualifications described above.

Although most terms of rating are common to all protective systems, their application depends upon the class and, in consequence, examples of rating are given best under the heading dealing specifically with each. In all cases the rated stability factor is the minimum factor and the rated fault settings are the maximum settings at full load.

Merits and Limitations. The first consideration in the choice of a feeder protective system may lie in deciding the most appropriate class from which to select it, and

for guidance in doing this the broad merits and limitations of each are given below—

Time-graded Class. Good systems in this class—

1. Save capital expenditure on pilots.
2. Provide quite good to fairly good discrimination. depending upon application and type of main (e.g. radial or ring feeder).
3. Provide back-up protection.

But—

(*a*) Have limited application to any network.

(*b*) Cause increased stress on plant and network by time-delayed operation.

(*c*) All require voltage transformers for ring main protection.

Distance Class. Good systems in this class—

1. Save capital expenditure on pilots.
2. Can provide good discrimination.
3. Have reasonably short time delays.
4. Provide back-up protection.

But—

(*a*) Require voltage transformers.

(*b*) Their application is restricted to reasonably long lines.

(*c*) Cause stress on plant and network by short time delay in operation.

Special Mains Class. Good systems in this class—

1. Save capital expenditure on pilots.
2. Provide unit protection.
3. Can provide excellent discrimination.
4. Can give instantaneous operation.
5. Function without voltage transformers, i.e. on current only.
6. Can possess stability with low fault settings.

But—

(*a*) Involve additional capital expenditure on special mains.

(*b*) Some involve transposition of cores at certain cable joints.

(*c*) Some involve use of special switchgear.

(*d*) Some require an auxiliary supply of energy.

(*e*) Some are limited by voltage of network.

Feeder Arrangement Class. Good systems in this class—

1. Save capital expenditure on pilots.
2. Provide unit protection.
3. Can provide very good discrimination.
4. Can provide instantaneous operation.

But—

(*a*) Have limited application.

(*b*) Under certain conditions require back-up protection.

(*c*) Some require high fault settings.

(*d*) Some are not applicable to ring mains.

(*e*) Require voltage transformers.

(*f*) Some are subject to switching limitations.

Merz-Price Class. Good systems in this class—

1. Possess universal application to any network.
2. Provide ideal discrimination.
3. Provide unit protection.
4. Give instantaneous operation.
5. Function without voltage transformers, i.e. on current only.

But—

(*a*) Require capital expenditure on pilot cable.

Choice of Class. The most suitable protective system to adopt depends so much upon local conditions of

service and economics that every case requires individual consideration. As a general rule, however, the *Merz-Price* class offers the best protective systems because they possess universal application, instantaneous operation, and ideal discrimination, but within the limits of their application the *special cable* class offers similarly good systems.

The *feeder arrangement* class is useful when instantaneous operation is desired without pilot wires, and the *time-graded* class is always required for back-up protection. The *distance class* is useful where special mains, or arrangement of mains, or pilot wires are uneconomical on long extra high voltage transmission lines.

As a general rule, the capital cost of a protective system only becomes appreciable when a pilot or special cable is required, otherwise its cost is very small compared with the cost of the main it protects. Even with the cost of the pilot or special cable included the total cost is still a very small percentage of the capital value of the network protected. Broadly speaking, experience shows that the enhanced worth and reliability of a better but more expensive protective system secures economy in copper and continuity of supply to such a degree that the monetary saving from these items yields an adequate return on the capital expenditure entailed.

EARTHING OF NETWORKS

Faults and Earthing. Experience shows that on an average alternating current distribution network roughly 80 per cent to 90 per cent of the disturbances which occur is due to earth faults. The protection of mains from this class of fault is, therefore, of primary importance and necessitates some form of permanent earthing of the network, so that when an earth fault

occurs a current may flow for operating the various protective systems.

Earthing of the neutral point in a three-phase network, the common point in a two-phase three-wire network, and one wire in a single-phase network, is now the generally accepted practice in this country.

Reduced Stress. In the generally employed three-phase network, the usual practice is to earth the neutral point of a generator or transformer through a resistor as shown in Fig. 5, so that the network and plant are relieved of unnecessary stress during a fault to earth. There are three ways in which the stress is reduced by the use of an earthing resistor in this way. Firstly, it lessens the voltage rise to earth which takes place on the remaining healthy phases of the network, thus limiting the stress imposed upon any weak spots in the insulation of the other phases and reducing the risk of development of a further fault. Secondly, it limits the fault current to a desirable value, thus lessening the damage to the faulty unit and the stress imposed upon the circuit breakers which isolate it. Thirdly, by causing a fault current to flow in the main, it provides a means for operating a protective system so that the faulty unit may be isolated immediately under easy conditions.

When a fault to earth occurs on an insulated system, on the other hand, unless the faulty unit is isolated manually from the network, operation of the protective system will not take place until another phase fails to earth, and then isolation of the faulty units occurs under the severe condition of a between-phase fault.

With a resistance-earthed network it is found that earth faults can, in the majority of cases, be cleared as such. There are, however, isolated cases in which the easement due to the earthing resistance is negatived

by simultaneous earth faults occurring on different phases of the network, as shown in Fig. 5.

Rating. The most suitable ohmic rating for the earthing resistor depends upon local conditions of service and each case requires individual consideration upon the following general principles.

The first consideration is the amount of fault current that should be allowed to flow.

The chief advantage of keeping this small is to reduce the current stress in the network, plant and switchgear to a minimum under fault conditions. Notwithstanding this, however, the balance lies in favour of allowing a reasonably heavy fault current to flow because it causes windings in plant to be more adequately protected; the voltage and transient voltage stress on plant and network to be reduced; the margin of safety in fault current over the fault setting of the protective systems to be increased, and the fault to be more easily located.

The earth fault current affects the degree to which transformer or generator windings are protected in a manner given by the following rule—

If X = the fault setting of the protective system expressed as a percentage of the full load current of the plant protected;

Y = the amount of winding protected in the plant from the end remote from the neutral point expressed as a percentage of the total winding, and

Z = the earth fault current expressed as a percentage of the full load current of the plant.

Then—

$$\text{The earth fault current } (Z) \text{ required} = \frac{100\,X}{100 - Y}$$

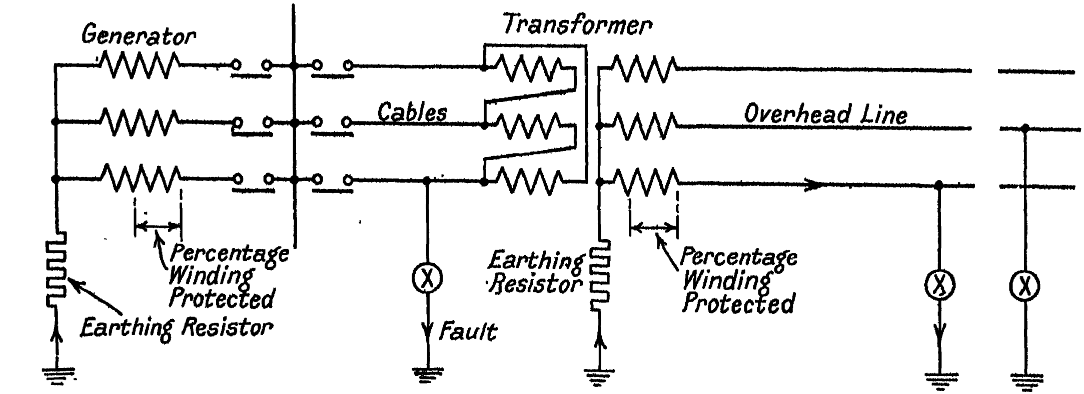


FIG. 5. TYPICAL EARTHING OF NETWORKS

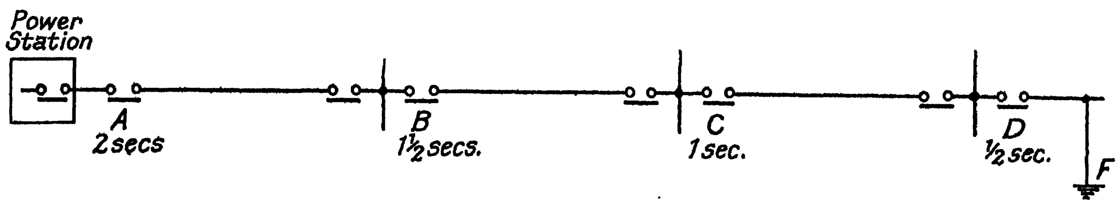


FIG. 6. PRINCIPLES OF TIME GRADING FOR RADIAL FEEDERS

or, the amount of winding protected (Y) for a given earth fault current $= \dfrac{100\,(Z - X)}{Z}$

Having decided the most suitable fault current value, the ohmic rating of the earthing resistor is determined from the voltage of the network; the resistance of the earth plate (which may be from 1 to 4 ohms, depending upon its type, the class of soil, and its condition); and the impedance of the return path for the fault current from the most remote part of the network. In any case, the ohmic value of the whole earth fault circuit should never exceed a value which fails to pass a current of at least 50 per cent in excess of the highest fault setting of the protective systems installed on the network.

In practice, a current rating of 500 amp. for 30 sec. is a representative value for an earthing resistor of a modern network, increasing to 1000 amp. in the case of the larger networks, and up to 2000 amp. in certain cases. On extra high voltage networks above 66 kV the neutral point is often dead-earthed, chiefly in order to reduce the dielectric strength required in the insulation and the reduction this makes in the cost of the plant, switchgear, and network.

THE TIME-GRADED CLASS

As the above heading implies, protective systems in this class obtain their discrimination by time grading, and depend for operation upon abnormal currents, such as overcurrents or leakage currents. They have been evolved as an improvement upon protection by fuses. Two of their advantages are that no pilot wires are required and that they can provide back-up protection.

Radial Mains. Fig. 6 shows a single power station with a radial feeder network, the relays A, B, C, and D

having various time lags ranging from $\frac{1}{2}$ sec. at D to 2 sec. at A, so that a fault at F causes operation of switch D first and switches A, B, and C are prevented from operating by a time interval for stability. The stress imposed upon the plant is a maximum for a fault adjacent to relay A which has the maximum time delay. The number of feeders that can be so protected depends upon the maximum time delay permissible.

Fig. 7 shows a typical stability diagram for feeders AB, BC, and CD of the network in Fig. 6, from which it will be seen the stability factor at A =

$$= \frac{\text{time setting of relay } A}{\text{time setting of relay } B + \text{operating time of switch } B}$$

$$= \frac{2}{1{\cdot}75} = 1{\cdot}14.$$

The stability factors for B and C are obtained in a similar way, giving stability factors of 1·2 and 1·33 respectively. A constant stability factor (for example 2) would be desirable, but is not possible because of the limit imposed by the maximum time delay permissible at the power station.

Ring Mains. When time-graded protective systems are applied to ring mains it is necessary to take into account the direction of the flow of power to the fault and to grade in both directions round the ring. For this purpose relays are used as shown in Fig. 8, which operate at a given current value for a power flow from the busbars into the main. The relays A, B, C, D, and E, are required to operate in the times shown when power flows around the ring in a clockwise direction, whilst relays F, G, H, I, and J are required to operate when power flows around the ring anti-clockwise. It might appear that directional relays are required for each switch, but actually it is only necessary for the switches with the shortest time lag in any

substation to be so equipped. Thus, considering relays *D* and *H* in Fig. 8, when fault current flows clockwise

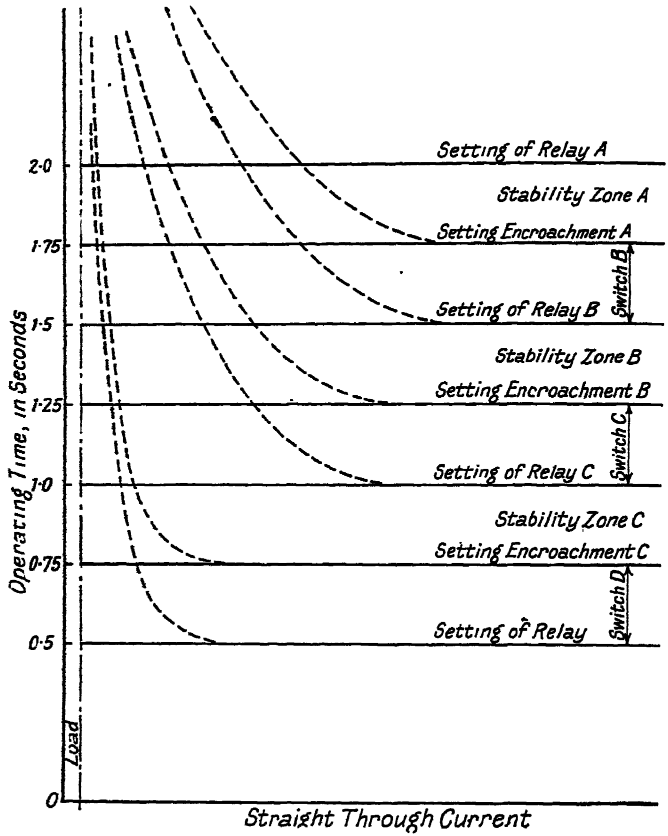


FIG. 7. STABILITY DIAGRAM FOR TIME-GRADED PROTECTIVE SYSTEMS

the non-directional relay *H* is inoperative by its longer time setting, and when the fault current flows anti-clockwise relay *D* is inoperative by its directional

feature. The stability diagram for grading in each direction round the ring main is similar to Fig. 7.

OPERATION

Time-graded protective systems operate either by overcurrent or by leakage current, or a combination

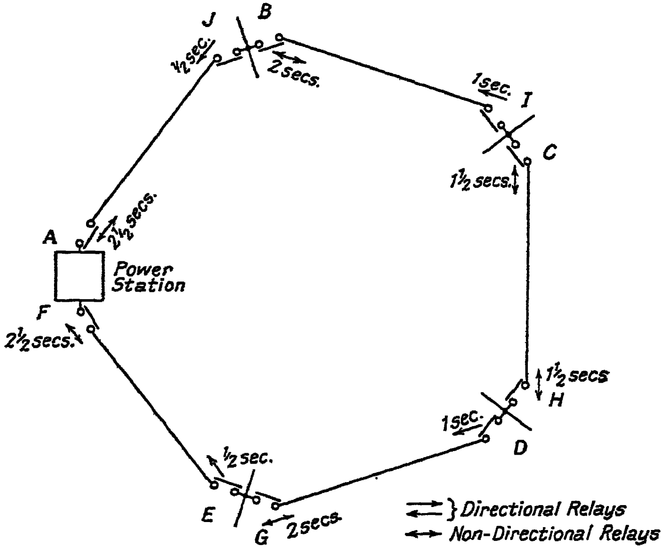


FIG. 8. PRINCIPLES OF TIME GRADING FOR RING MAINS

of both. Trip coils of switches may be operated direct from current transformers provided sensitivity and a directional feature are not required. Following are some methods adopted to obtain operation from such currents.

Core Balance.* This consists of a current transformer through which the multiphase conductors of the main are passed, as shown in Fig. 9. Particular

* Ferranti-Field.

care must be taken to ensure that the return earth fault current does not flow through the transformer by way of the lead sheath of the cable and so neutralize the magnetic effect in the core. To prevent this the lead sheath is earthed on the cable side of the current transformer as shown.

Earth Leakage. This consists of three current transformers (one per phase) having their secondary windings starred at each end, as shown in Fig. 10. The protective relay is connected between the star points, and any out-of-balance in the currents in the main is reflected in the relay or trip-coil circuit.

Overcurrent and Earth Leakage. This is a combination of the ordinary overcurrent and earth leakage connections already described, and is illustrated in Fig. 11. It is common practice to employ one relay containing two overcurrent elements and one earth leakage element.

"Z" Connection. This scheme is illustrated in Fig. 12 and enables two relays or trip coils to be operated from three current transformers, so that a fault condition on any phase causes one or other of the relays to operate. The only advantage of this connection is the economy effected by eliminating one relay element or trip coil. The disadvantages are the variable fault settings, dependent upon the phase or phases overloaded, the phase relationship between the load and fault current, and the difficulty of obtaining a common point at which to earth the secondary circuit.

Voltage Connections. A voltage supply is required for operating directional relays, and to ensure operation with fault currents at a bad power factor the voltage is arranged to lag behind the current in the current coils of the directional overcurrent relays by 30 degrees.

Directional leakage relays require a voltage supply proportional to the residual voltage to earth which can

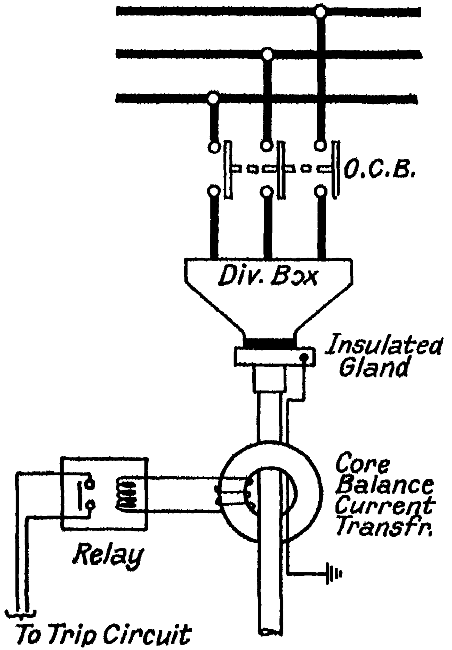


FIG. 9. CORE BALANCE PROTECTIVE SYSTEM

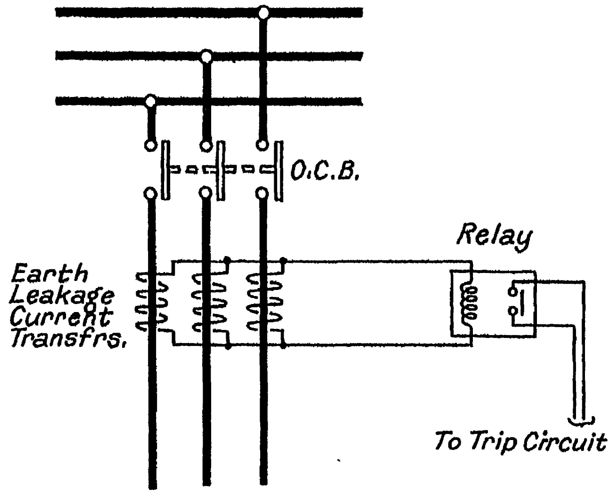


FIG. 10. EARTH LEAKAGE PROTECTIVE SYSTEM

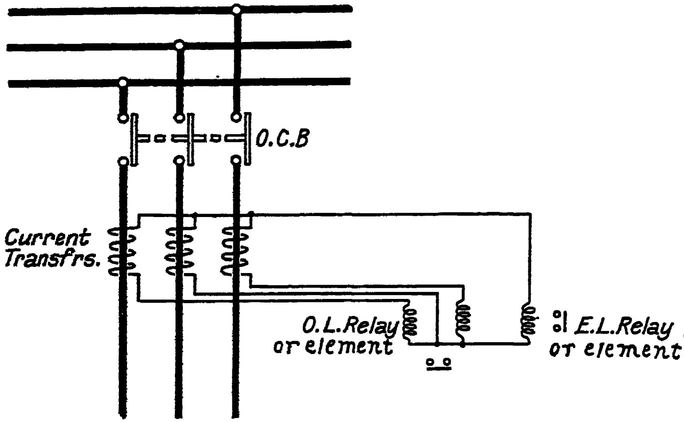


FIG. 11. OVERCURRENT AND EARTH LEAKAGE PROTECTIVE SYSTEM

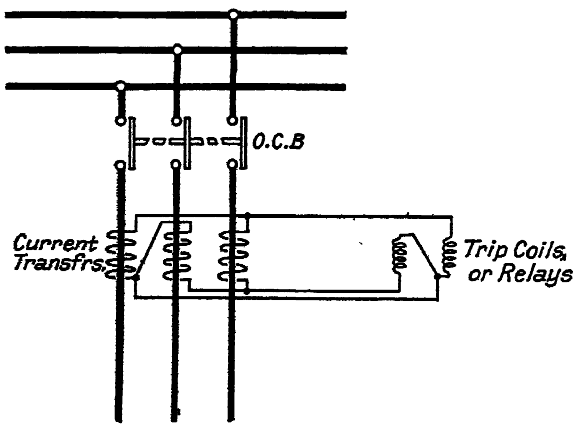


FIG. 12. "Z"-CONNECTED OVERCURRENT PROTECTIVE SYSTEM

be obtained from a voltage transformer having an open delta secondary winding, as shown in Fig. 13. The voltage coils of overcurrent relays can be energized

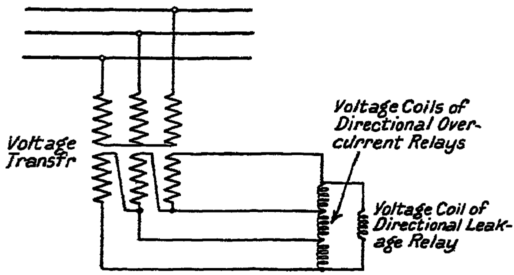


FIG. 13. STAR-DELTA VOLTAGE TRANSFORMER

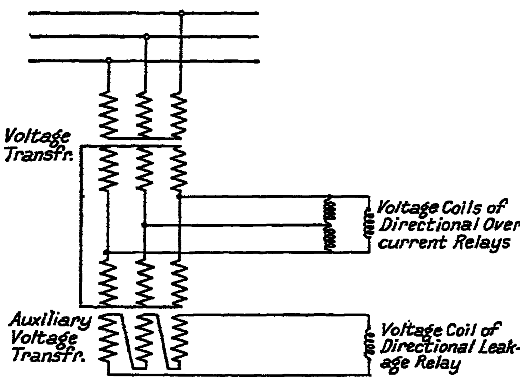


FIG. 14. STAR-STAR VOLTAGE TRANSFORMER WITH AUXILIARY TRANSFORMER

from the same transformer. Fig. 14 shows an auxiliary voltage transformer with a delta-connected secondary for use with a star-star voltage transformer.

Discrimination. The following are typical methods by which protective systems in this class obtain their discrimination.

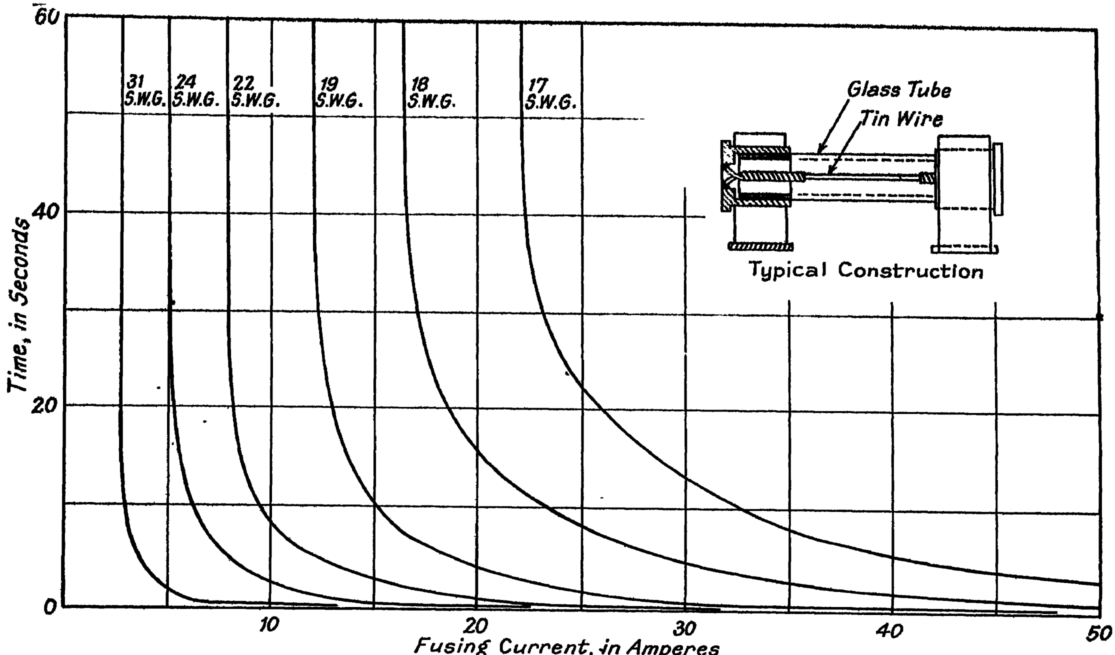


FIG. 15. CHARACTERISTIC CURVES FOR TIME LIMIT FUSES

Fuse. One of the earliest methods of obtaining a time delay was to short-circuit the trip or relay coils with a fuse.* This gives a time lag which is inverse

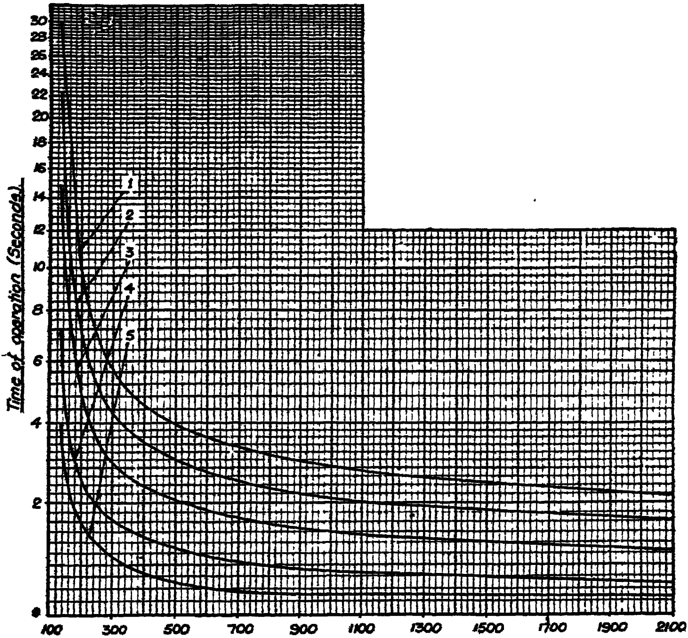


FIG. 16. CHARACTERISTIC TIME-LOAD CURVES WITH VARIOUS SETTINGS
Metropolitan-Vickers type P.B. relay

with respect to the overcurrent as shown by the typical characteristic curve (Fig. 15). This method fails to give complete discrimination because with heavy overcurrents all the fuses blow instantaneously.

Inverse Definite Time Limit Relays. To overcome the disabilities of the fuse, relays were developed having

* Oxley.

inverse characteristics, but with a definite time delay, as illustrated in Fig. 16, which shows the characteristics of the Metropolitan-Vickers Type P.B. relay. The definite minimum time delay enables time grading to be obtained, as shown on the stability diagram (Fig. 7). The effect of the inverse characteristic of the relay is shown dotted.

The P.B. relay (Fig. 17) operates upon the induction principle, and the definite minimum time characteristic

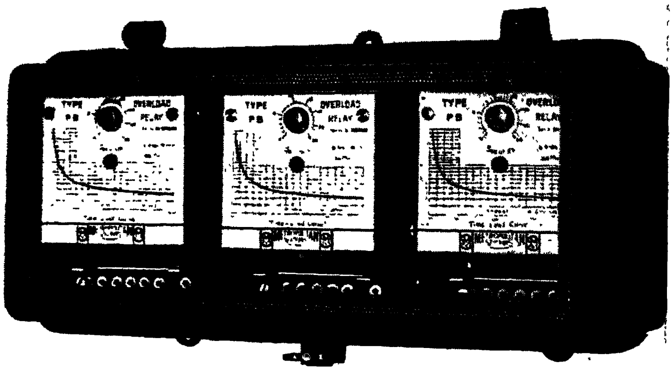


FIG. 17. METROPOLITAN-VICKERS TYPE P.B. INVERSE TIME LIMIT OVERLOAD RELAY

is obtained by means of a transformer which becomes saturated as the overcurrent increases, thus limiting the forces operating the relay. The current setting is adjusted by plugging in to a suitable tapping on the primary of the transformer which saturates. The time setting is adjusted by varying the distance through which the contact-making device travels.

Fig. 18 illustrates a relay* made by Almanna Svenska Elektriska Aktiebolaget, which has characteristics similar in principle to those shown in Fig. 16. One of

* W. H. Petersen.

the special features is that the induction disc is constantly rotated by the load current, but initiates a

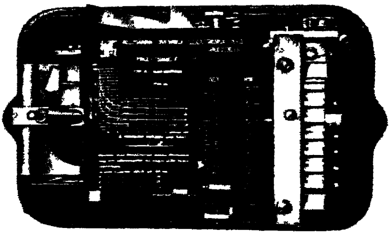


FIG. 18. A.S.E.A. INVERSE TIME LIMIT OVERLOAD RELAY

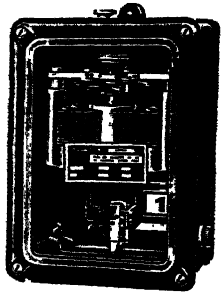


FIG. 20. NALDER-LIPMAN DIRECTIONAL RELAY

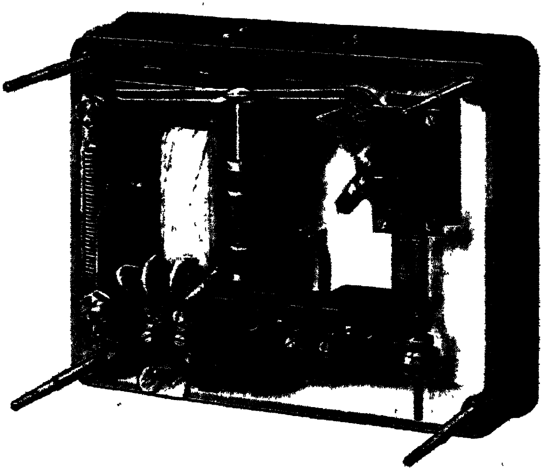


FIG. 19. REYROLLE DEFINITE TIME LIMIT RELAY

tendency to operation only when a predetermined overcurrent value is reached. A further feature is an

instantaneous release which can produce operation if desired for very heavy predetermined overcurrents.

Definite Time Limit Relay. With relays of this type the time delay is independent of the fault current. They usually operate as auxiliary relays to instantaneous overcurrent and/or leakage relays. Fig. 19

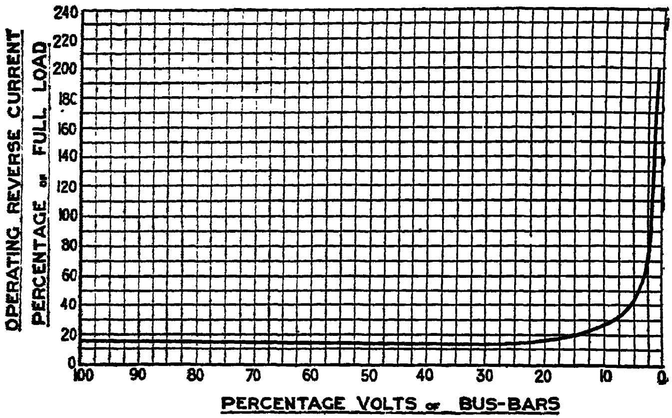


FIG. 21. CURVE OF VOLTAGE COMPENSATION FOR NALDER-LIPMAN DIRECTIONAL RELAY

shows the Reyrolle definite time limit relay* in which the timing is obtained accurately by means of a pendulum which controls the contact-making device through a clockwork escapement. The relay is operated electrically from the tripping battery and can be made to reset instantaneously or otherwise.

Directional Relays. Directional relays which are required for ring mains and interconnectors are usually of the induction type and should be compensated for fall in voltage and low power factor. Fig. 20 illustrates a type of directional relay† introduced by Nalder Bros. &

* J. M. Mirrey and B. H. Leeson.
† C. L. Lipman.

Thompson, Ltd., in which the moving portion consists of a cylindrical cup in place of the more usual disc. The current coil is situated inside the cylindrical cup and the voltage coil excites the main field surrounding it on the outside. The magnetic fields produced by these coils interact on the well-known wattmetrical principle causing rotation. The construction reduces losses and for a given robustness increases the sensitivity. Fig. 21 shows a characteristic curve of the variation of operating current with voltage.

Rating. A typical rating for a time-graded system is as follows—

Protective system	Overcurrent and earth leakage
Network	Three-phase resistor earthed neutral
Network Voltage	6600 volts
Network frequency	50 cycles
Number of mains in series	4
Type of main	Radial
Normal load	150 amp.
Current transformer ratio	200/5
Earth fault setting	40 amp.
Phase fault setting	400 amp.
Overcurrent and leakage relay. Type	Three-pole instantaneous self-resetting
Overcurrent setting range. Two-pole	3 to 15 amp.
Leakage setting range. One-pole	·75 to 4·5 amp.
Time-grading relay. Type	Definite time limit
Time-grading relay consumption	30 volts, 1 amp. direct current
Time setting range	0/5 sec.
Switch operating time	0·25 sec.
Time interval for grading	0·5 sec.
Maximum time setting	2 sec.
Stability factor	1·14 minimum 1·33 maximum
Tripping circuit	30 volts, 3 amp., direct current

THE FEEDER ARRANGEMENT CLASS

Protective systems in this class have been evolved to obtain discriminating protection without the use of

pilot wires or time grading, and, as the title indicates, they are not applicable to ordinary single mains.

The majority of systems depend upon two or more identical mains being available, and are known generally as parallel feeder protective systems because they are only applicable to two or more identical mains or feeders connected in parallel, by which the total load is shared equally. The protective systems obtain their discrimination from the balance or out-of-balance which exists between these two or more currents measured at the same end of the mains.

The systems described offer good protection under suitable conditions and are in general use.

Parallel Feeder Protective System. Fig. 22 shows a typical system suitable for feeders where power may be fed in both directions. Its chief feature is the employment of differentially connected directional relays.* Two relays are connected across normally equipotential points of 200/5 current transformers which are connected up on the current balance principle explained earlier. The arrows show current fed from a power station to a substation with a load of 300 amp., and under the healthy condition of 150 amp. in each feeder the protective systems at each end remain balanced.

With a fault at *X* operation takes place, and completely isolates feeder *BD* as follows. At the power station end the fault current flowing through *B* exceeds that flowing through *A*, and the secondary current, which is proportional to the difference between the two, flows in a direction which only operates relay and switch *B*. At the substation end the fault current flowing through *D* is equal to the fault current flowing through *C*, except that it flows in the opposite direction, and the secondary current, which is proportional to

* E. B. Wedmore

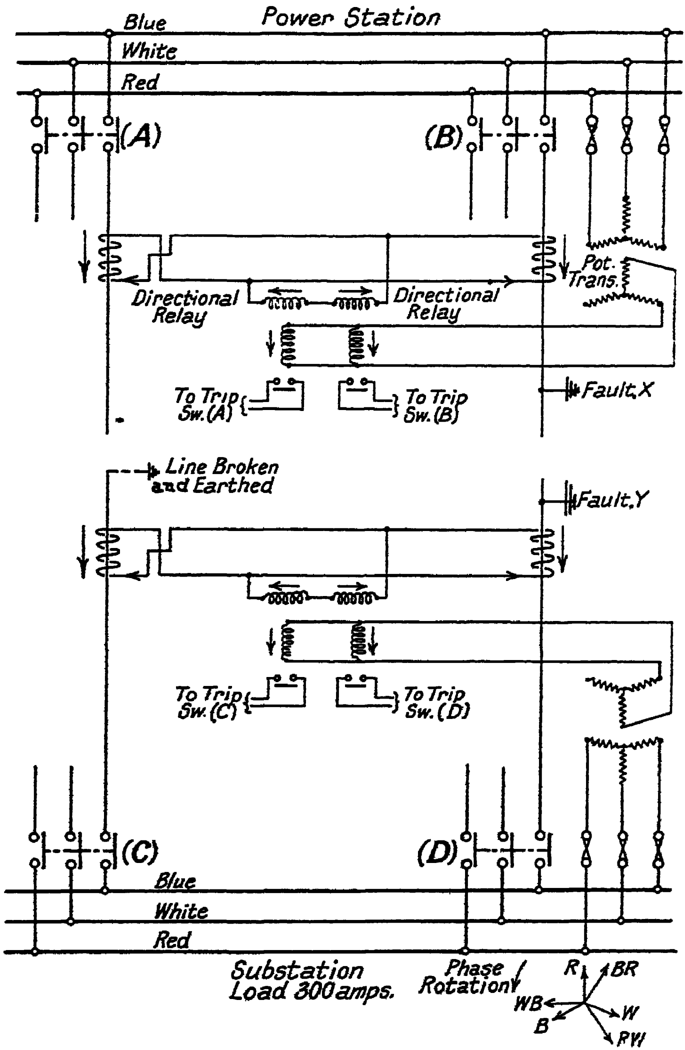


FIG. 22. PARALLEL FEEDER PROTECTIVE SYSTEM WITH DIFFERENTIALLY CONNECTED DIRECTIONAL RELAYS

the sum of the two, flows in a direction which only operates relay and switch D.

With a fault at Y equal current may flow through A and B, and, in consequence, both switches remain closed. The fault, however, is fed through feeder A, C, and D, which causes relay and switch D to operate as described for the fault at X. The opening of switch D causes the fault current to flow through B only, which operates the relay and switch B, thus completely isolating the faulty feeder.

Referring to a typical stability diagram (Fig. 23), there are two conditions under which such a protective system must have stability. The first condition is the usual encroachment due to a straight-through fault current, and the tendency to inadvertent operation consists of the protective-transformer and feeder out-of-balance effects. The second and more severe condition is when one feeder is out of commission (either by correct operation of the protective system or by the manual operation of a switch) and the other feeder carries an overcurrent of 300 amp. which forms a direct out-of-balance effect. Since these two conditions cannot occur simultaneously, the no-load fault setting is based upon the second with a small stability factor to reduce the maximum value of the variable fault setting explained below.

For a fault at X (Fig. 22) the fault setting equals 400 amp. Similarly, the fault setting for a fault at Y is 400 amp. to operate switch D, but to operate switch B it equals the load current plus the no-load fault setting or about 700 amp., the actual value being something less, depending upon the phase relationship of the two currents.

To secure correct operation, therefore, the earthing resistance must allow an earth fault current in excess of 700 amp. to flow for a fault at Y. For example, if

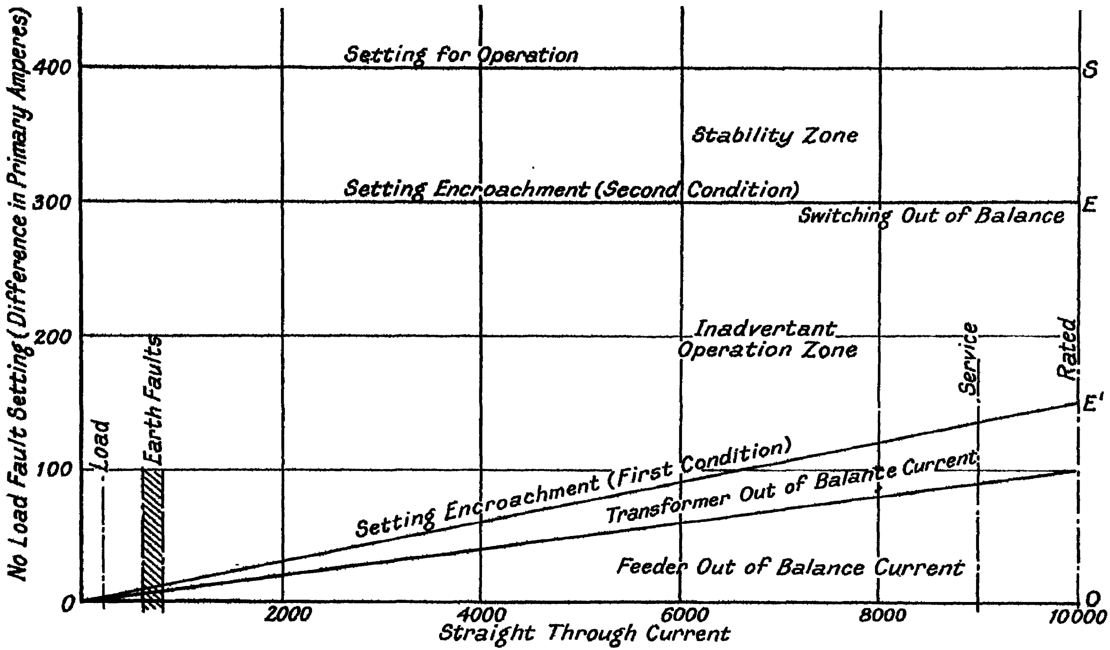


Fig. 23. Stability Diagram for Parallel Feeder Protective System with Differentially Connected Directional Relays

only 500 to 600 amp. is passed, then switch *D* will clear for a fault at *Y*, but switch *B* will not do so and the fault condition will persist. In certain cases this condition may arise in practice, and to provide for it and the protection of one feeder individually, it is usual to instal back-up protection in the form of over-current relays with a small definite time lag.

Parallel feeder protective systems are not ideal, and their most advantageous application is to cable networks. If they are applied to overhead transmission lines, wrong discrimination may be given, for example assuming the line *AC* to be broken and earthed on the load side, then switch *A* will be left closed and the healthy line *BD* is isolated wrongly.

In the system just described, stability can only be secured by high fault settings determined in accordance with the second condition (Fig. 23), because if they are reduced materially any switching operation will produce inadvertent operation. Switching the protective system in or out of commission by auxiliary switches, operated either automatically by the circuit breakers or by hand, is not a satisfactory alternative solution to the problem of obtaining stability.

Surge-proof Parallel Feeder Protective System. This system, introduced by the Reyrolle Company, employs an auxiliary, or surge-proof relay,* which renders it proof against out-of-balance load surges caused by switching operations and enables a larger stability factor to be obtained with much lower fault settings. Without the surge-proof relay the system would require a directional relay setting in excess of the load current, similar to the second condition already described for stability diagram, Fig. 23. With a surge-proof relay, however, the directional relay setting is determined in relation to the smaller out-of-balance current due to

* G. H. Gardner and C. C. Gallop

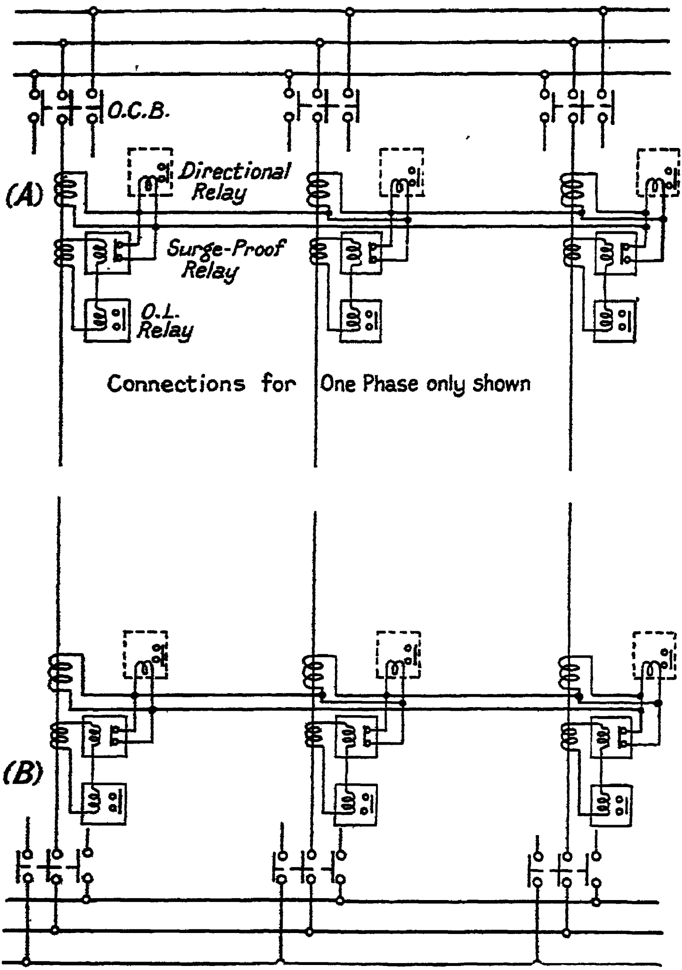


FIG. 24. SURGE-PROOF PARALLEL FEEDER PROTECTIVE SYSTEM

the transformers and feeders in accordance with the first condition in Fig. 23.

Fig. 24 shows the application of the surge-proof relay to a well-known form of parallel feeder protection suitable for any number of feeders or interconnectors where the power may flow in either direction. The secondaries of the current transformers on the same phase of each feeder are connected up in series so that a single-phase current can circulate. The corresponding single-phase element of the directional relays protecting each feeder are connected as shown, so that under a healthy condition, when the total load is shared equally between the feeders, the relays are inoperative. When a fault occurs an out-of-balance current flows in such a direction that only the directional relay protecting the faulty feeder at each end is operated.

The surge-proof relays are of the overcurrent type, set to operate at 10 per cent full load, and, when de-energized, each instantaneously short-circuits its protective current transformer and directional relay. When energized, they have a small inverse time lag to prevent inadvertent operation by feeder capacity surges. It will be clear from this and the diagram that the directional relay and transformer at either end of one feeder cannot be effective in the secondary circuit of its protective system until the feeder is completely switched in and carries its share of load in excess of 10 per cent full load. This enables a feeder or feeders to be switched in or out with impunity. Although on very light loads the load current may be insufficient to operate the surge-proof relay, a fault will do so as soon as it occurs, and will allow the directional relay to operate unimpaired.

A typical stability diagram (Fig. 25) shows the worst case of two feeders only and represents a stability factor of $1\frac{1}{2}$. The stability factor for the given fault

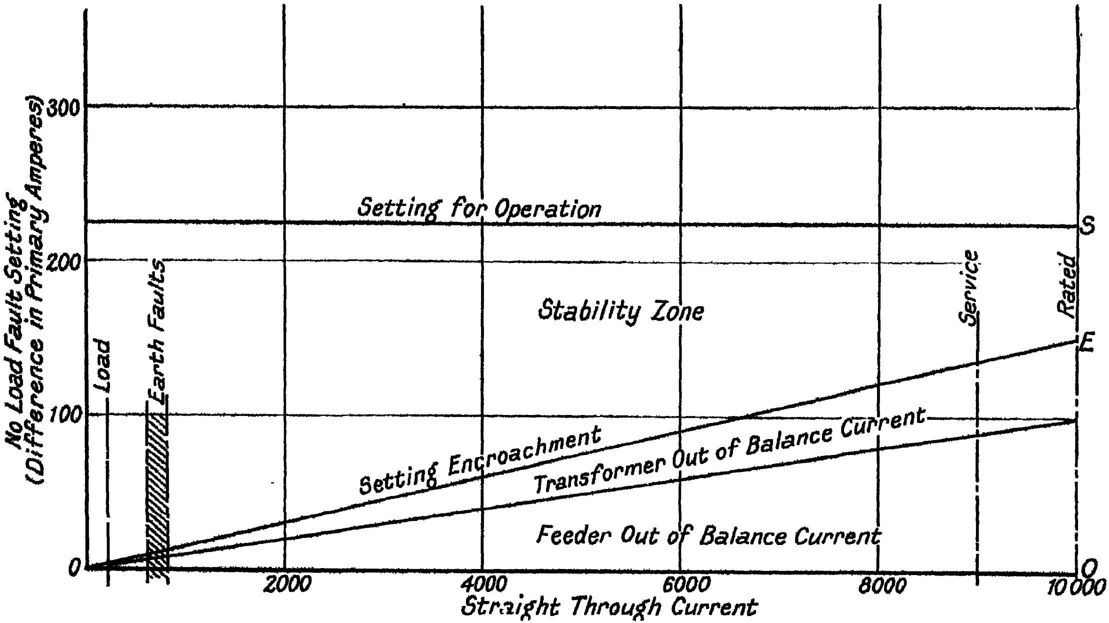


FIG. 25. STABILITY DIAGRAM FOR SURGE-PROOF PARALLEL FEEDER PROTECTIVE SYSTEM

setting improves as the number of feeders increases and when three are in commission it equals 2. The protective relay setting is constant, but the fault setting is variable for reasons already described.

Other Protective Systems. Further examples of improved parallel feeder protective systems are the Metropolitan-Vickers translay system, which uses a translay relay (Fig. 53); the B.T-H. bias system, which uses a biasing transformer (Fig. 60); and the G.E.C. parallel feeder system, which uses a beam relay (Fig. 48).

Rating. A typical rating for a parallel feeder protective system is as follows—

Protective system	Surge-proof.
Network	Three-phase resistor earthed neutral
Network voltage	22,000 volts
Network frequency	50 cycles
Length of main	7½ miles
Number of mains	3
Normal load of each main	150 amp.
Nominal load of each main C.T. ratio	200/5 amp.
Straight-through current. Total	10,000 amp.
Earth fault setting. All phases. No load	225 amp.
Earth fault setting. All phases. Loaded	525 amp., nominal
Phase fault setting	Same as earth fault settings
Directional relay setting	5·625 amp.
Directional relay time setting	Inverse
Surge-proof relay setting	·5 amp.
Surge-proof relay time setting	Operation—inverse; reset—instantaneous
Stability factor—	
Two feeders	1·5
Three feeders	2
Tripping circuit	30 volts, 3 amp., direct current

THE MERZ-PRICE CLASS

The stress imposed upon networks and plant under fault conditions, and the liability of synchronous plant to fall out of step, depend upon the time taken to isolate the faulty unit. Thus, fundamentally, it is undesirable

to obtain discrimination by time grading, and in service it is necessary to limit the maximum time for operation of the overcurrent time-graded systems to about 2 sec., depending upon local conditions. This imposes a definite limitation upon the number of mains which can be so protected because each protective system must have a definite quota of time allocated to it and, in practice, it is no uncommon thing to "run out of time" with consequent negative stability factors and inadvertent operation. To improve upon this, the principle of parallel feeder protection with double current relays was extended by the aid of pilot wires to compare the current at one end of a main with that at the other.* With faults fed both ways, however, the fault setting approached infinity as the fault currents approached equality.

To overcome these disabilities a unit protective system was developed which also abolished the use of time for discrimination, and substituted the principle of differentially balancing over pilot wires, the current entering a main at one end with that leaving it at the other.† This opened up the development of protective systems requiring no voltage transformers, and having instantaneous operation, unrestricted application, and ideal discrimination. These are known as Merz-Price systems, and are most extensively used.

General Principles. There are two methods of pilot-wire balancing in use known respectively as *voltage balance* and *current balance.* Fig. 26 shows the principle of voltage balance. The secondaries of current transformers, one at each end of the main, are connected in series with pilot wires and relays, so that under healthy conditions their opposed voltages balance and no current flows to operate the relays.

* R. C. Clinker, E. B. Wedmore, and J. Whitcher.

† C. H. Merz and B. Price.

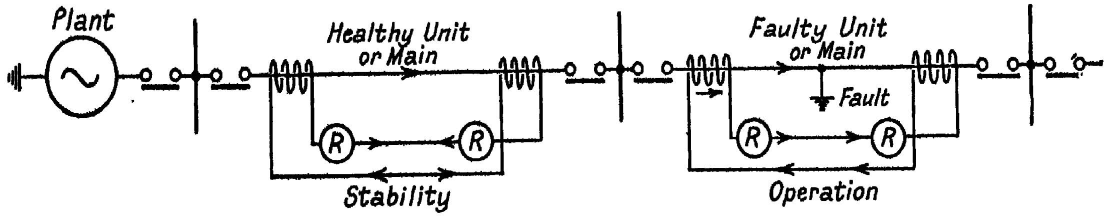


FIG 26 PRINCIPLE OF VOLTAGE BALANCE

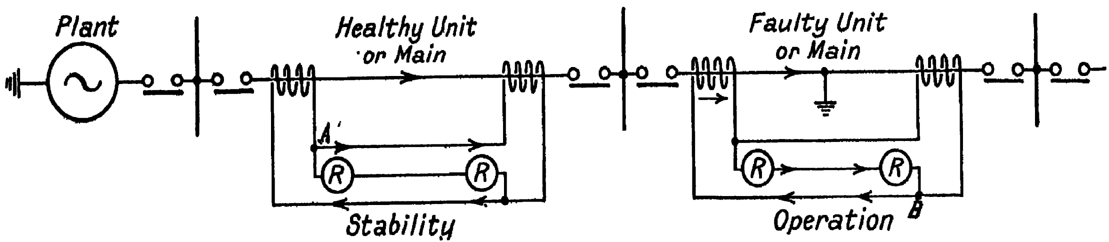


FIG 27 PRINCIPLE OF CURRENT BALANCE

For a fault fed one way as shown, one transformer generates a higher secondary voltage than the other, and the voltage difference causes a current to flow and operate the relays.

For a fault fed both ways, the transformer voltages no longer oppose but become additive, thereby intensifying the out-of-balance current operating the relays.

Fig. 27 shows the principle of current balance, in which ordinary current transformers have their secondaries connected to the pilots so that a current circulates when load or straight-through current flows in the protected main. When the main is healthy and each current transformer produces an equal amount of secondary current, *A* and *B* are equipotential points and no current flows in the relay circuit. When the main is faulty, the current transformers no longer produce equal or balanced currents, and, depending upon whether the fault is fed one way or both ways, the difference, or sum, of the two currents flows through the relays and can operate them.

Classification. Instead of grouping the representative protective systems to be described in this class under the two broad headings of current and voltage balance, they are classified by their normal frequency stability diagram (as shown in Fig. 28), as this enables the principles upon which they function to be more easily understood.

Normal Frequency Stability. In Merz-Price systems this depends upon the maintenance of a good balance in the pilot circuit under all conditions of service. Actually, in practice, out-of-balance currents encroach upon the relay setting and tend to produce inadvertent operation under straight-through fault conditions. Fig. 29 shows a typical stability diagram in which the out-of-balance currents are governed by the straight-through current. The four ordinates shown represent

TYPE OF STABILITY DIAGRAM (Normal frequency) . .	A		B		C		D	
FAULT SETTING .	Constant		Variable		Graded		Variable	
RELAY SETTING .	Constant		Biased		Constant		Constant	
BALANCE . .	Voltage	Current	Voltage	Current	Voltage	Current	Voltage	Current
REPRESENTATIVE SYSTEM . .	Sheathed pilot	B.T-H. self-compensating	Reyrolle Tee'd	G.E.C. beam relay	Reyrolle two-core diverter relay		B.T-H. bias transformer	Reyrolle E.H.V. split pilot
	Mock pilot	Reyrolle split pilot	Metro-Vick translay					

FIG. 28. CLASSIFICATION OF MERZ-PRICE CLASS OF PROTECTIVE SYSTEMS

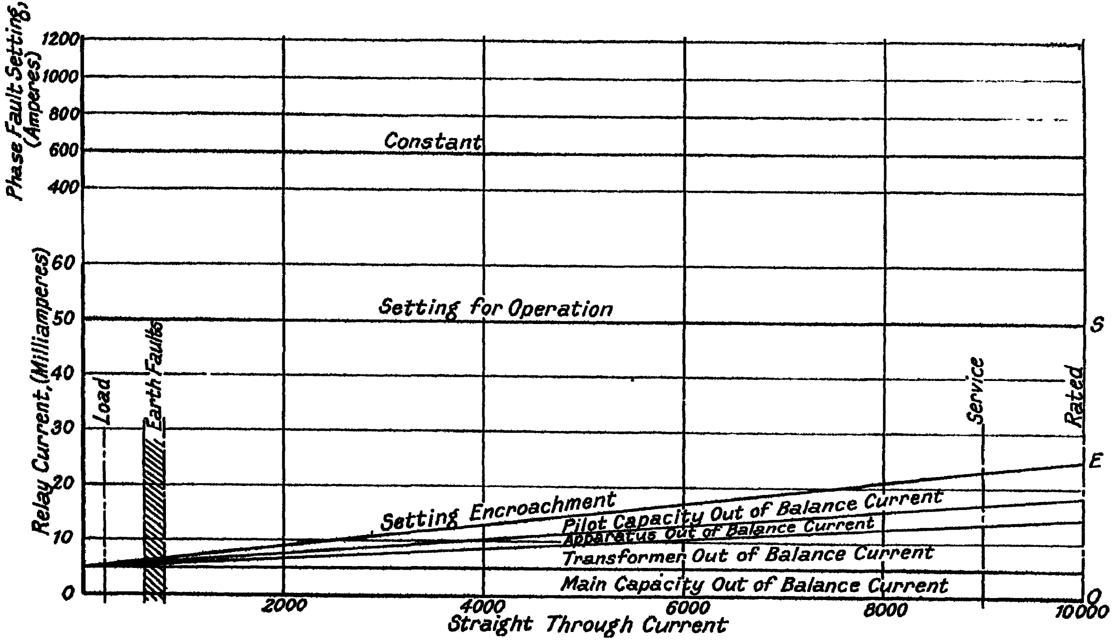


FIG. 29. NORMAL FREQUENCY STABILITY DIAGRAM FOR TYPE "A" MERZ-PRICE PROTECTIVE SYSTEMS
(Constant Fault and Relay Settings)

respectively the normal full-load current, the earth fault current as limited by an earthing resistor, the maximum straight-through current which can occur in service, and the straight-through current at which

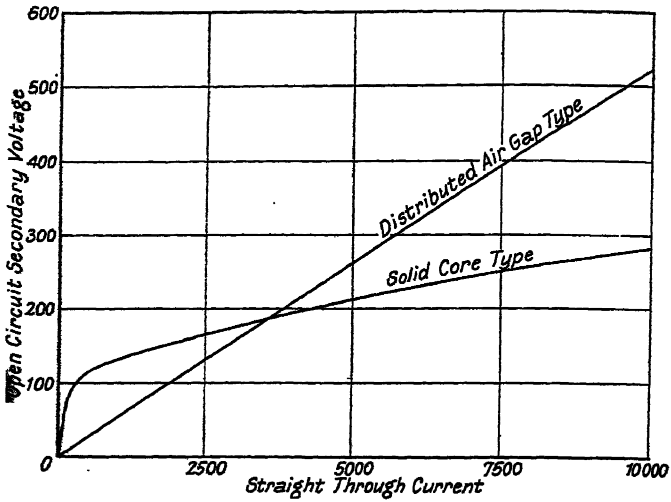


FIG. 30. CHARACTERISTIC OF CURRENT TRANSFORMERS FOR VOLTAGE BALANCE PROTECTIVE SYSTEMS

the protective system is rated. The causes of the out-of-balance currents illustrated are described below.

Transformers. There are two types of Merz-Price voltage balance transformers, the *solid-core* type and the *air-gap* type, which have characteristics as shown in Fig. 30. With the solid-core type it is difficult to get an accurate balance because the voltage characteristics depend upon the quality and state of saturation of the core. A balance to within plus or minus 4 per cent to 5 per cent is common and it is usual to incorporate some form of compensation for this error in the protective system. To improve transformer balance,

the Reyrolle Company developed first a single and then a distributed air gap* (D.A.G.) type of transformer, the core of which is shown in Fig. 31.

The great advantage is that transformers can be

FIG. 31. MAGNETIC CORE OF REYROLLE D.A.G. TRANSFORMER

manufactured and balanced to a definite standard because the voltage characteristic is a straight line, and to all practical purposes independent of the quality of the iron core which is never saturated. As an example of this a commercially produced transformer, when assembled within metal enclosures, is guaranteed to balance in voltage against a standard transformer to within plus or minus 0·4 per cent with 10,000 amp. straight-through current at 50 cycles.

Main Capacity Current. The charging current which

* J. M. Mirrey and F. Coates.

flows into a protected main at normal frequency is reflected into the pilot wire circuit as a pure out-of-balance current. Since its value depends upon the network voltage and size of the main, its effect remains constant irrespective of the straight-through current. There are no means of completely compensating for this out-of-balance, although protective systems to which type C and D stability diagrams are applicable go a long way towards it.

Pilot Capacity Current. The charging current which flows in the pilot wires at normal frequency forms a direct out-of-balance current which varies with the straight-through current. This current can be compensated for in various ways, as described later, and the value to be included in the stability diagram depends upon the efficiency of the compensation provided.

Apparatus. Certain protective systems contain apparatus ancillary to the above, which also may cause out-of-balance currents varying with the straight-through current.

Stability Factor. A stability diagram like Fig. 29 determines the rated fault and relay settings for a given stability factor. The various out-of-balance currents are determined experimentally by tests which must be fully representative of actual service conditions. The stability factor as described earlier (Fig. 4) is taken on the ordinate which gives it a minimum value. As shown in Fig. 29, for a stability factor of 2, the relay setting must be such that

Stability factor

$$= \frac{\text{relay setting for operation}}{\text{relay setting encroachment}} = \frac{OS}{OE} = 2$$

A fault setting of 600 amp. corresponding to a relay setting of 50 mA is shown at the top of the stability diagram.

Oscillatory Frequency Stability. Investigations mentioned by Clothier* prove that the current flowing into a healthy main is only equal to the current flowing out of it, provided each is at normal frequency. During an arcing fault it is possible for the current flowing out of a main to be greater than the current flowing into it. This out-of-balance current is caused by the cable discharging over its whole length towards one end due to the capacity and inductance of the particular main and its associated network, and has a frequency equal to the natural period of oscillation of the network fault circuit as a whole. The value of such currents depends upon the length of line, the plant connected to the network, etc., but the whole subject is far too complicated to enter into in this book. These high-frequency out-of-balance currents in a main are reflected into the pilot circuit as a pure out-of-balance high frequency current, and unless a protective system is adequately compensated for their effects, inadvertent operation in service will sooner or later result.

Oscillatory Stability Diagram. A typical stability diagram for oscillatory out-of-balance currents is shown in Fig. 32. The line *FD* represents the oscillatory out-of-balance in terms of fault setting for a given frequency. The line *AE* represents the fault setting at which an uncompensated relay operates, and shows how inadvertent operation may occur through its crossing the line *FD*. Similarly, the line *GC* represents the setting of a compensated relay.

The oscillatory stability factor is taken on the ordinate which gives it a minimum value.

$$\text{The stability factor} = \frac{\text{fault setting for operation}}{\text{fault setting encroachment}}$$

The oscillatory out-of-balance currents can only be

* *I.E.E. Journal,* Vol. 63, 1925, page 440.

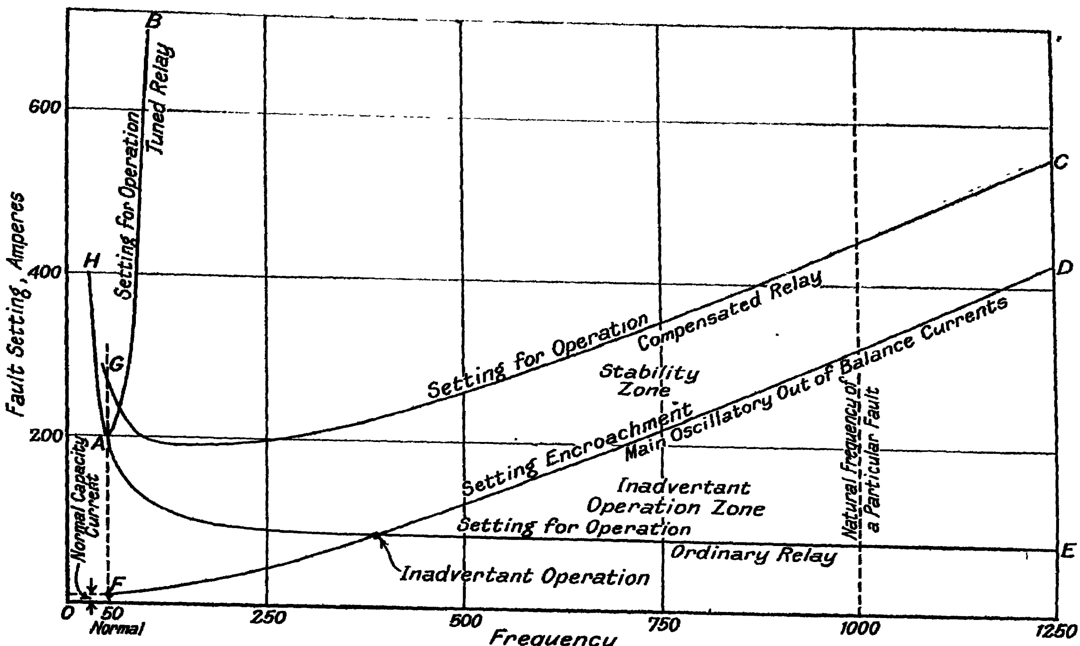


FIG. 32. TYPICAL OSCILLATORY FREQUENCY STABILITY DIAGRAM FOR MERZ-PRICE PROTECTIVE SYSTEMS

roughly estimated for given conditions. A change of network immediately affects their value and frequency, and hence it is necessary for the relay to be well compensated so that a large stability factor is obtained. Compensating a relay for frequency usually has the unfortunate effect of reducing its sensitivity, and hence

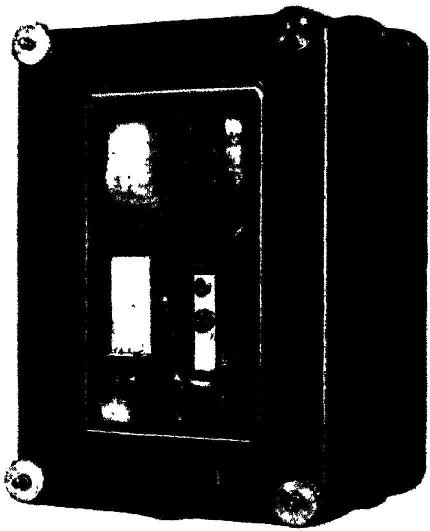


FIG. 33. REYROLLE MECHANICALLY TUNED RELAY

adequate oscillatory frequency compensation has the effect of increasing the normal frequency fault setting as shown at *G*.

Tuned Relays. What is practically equivalent to infinite stability for oscillatory out-of-balance currents can be obtained by the use of mechanically or electrically tuned relays or secondary circuits,* which were

* B. H. Leeson.

introduced by the Reyrolle Company. Fig. 33 illustrates a vibrating reed type of mechanically tuned relay which only responds to a frequency in the vicinity of 50, thus providing infinite stability. Relays of the mechanically-tuned type are also used by the B.T-H. Company in their bias and self-compensating protective

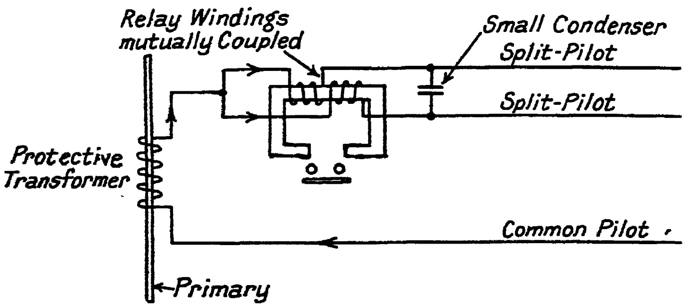


FIG. 34. REYROLLE ELECTRICALLY TUNED RELAY

systems. The relay setting *HAB* on stability diagram (Fig. 32) shows the characteristic of the electrically tuned type of relay (Fig. 34) employed in the split pilot protective system. This system provides infinite stability before the third harmonic frequency is reached, whilst at the same time it obviates any difficulty which might be experienced in the reed type of relay owing to crisp tuning and consequent non-operation on a small fall in frequency. In practice a drop in network frequency of 20 per cent and 10 per cent is accompanied by an increase in fault setting of only 20 per cent and 5 per cent respectively.

The use of tuned relays in place of compensated relays reduces the normal-frequency fault setting, especially in the electrically-tuned type, the impedance of which becomes purely resistive at normal frequency.

Rating. A typical rating of a Merz-Price system is as follows—

Protective system		Split pilot
Network		Three-phase resistor earthed neutral
Network voltage		33,000 volts
Network frequency		50 cycles
Length of main		10 miles
Normal load		200 amp.
Straight-through current		10,000 amp.
Transformers		D.A.G.
Turns ratio		400/1, 500/1, and 600/1
Earth fault setting:	*R*	150 amp.
	W	120 amp.
	B	100 amp.
Phase fault setting:	*R* and *W*	600 amp.
	B and *W*	600 amp.
	R and *B*	300 amp.
Relay setting		50 mA
Time setting		Instantaneous
Stability factor		2
Stability factor, oscillatory		Electrically-tuned relay
Tripping circuit		30 volts, 3 amp., direct current

If the fault settings are not given in detail the rated earth and phase fault settings are 150 amp. and 600 amp. respectively.

Pilot Cables. Although ordinary telephone wires of the Post Office type could be used for Merz-Price systems, this practice is not usually adopted owing to their frailty and low dielectric strength, and to the risk of wrong connections being made inadvertently when carrying out routine tests upon telephone type terminal boards.

The avoidance of financial loss and the maintenance of prestige depend so much upon the correct operation and stability of a protective system that it pays to put in special pilot cables. These pilot cables usually accommodate additional well-insulated "pairs" for the private telephone system of the electrical undertaking

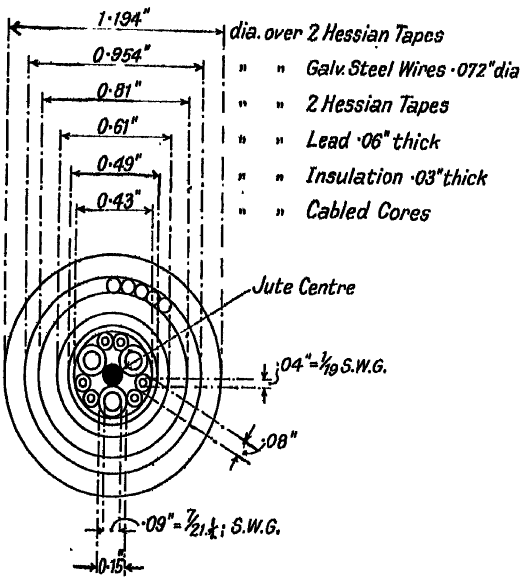


FIG. 35. PLAIN THREE-CORE PILOT CABLE WITH TELEPHONE PAIRS

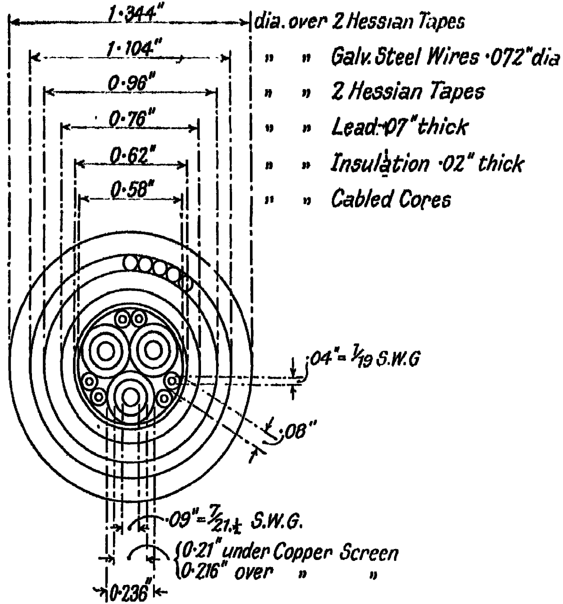


FIG. 36. MERZ-BEARD PILOT CABLE WITH TELEPHONE PAIRS

and are generally laid or installed at the same time as (and adjacent to) the main they protect.

Figs. 35, 36, and 37 show typical pilot cables which

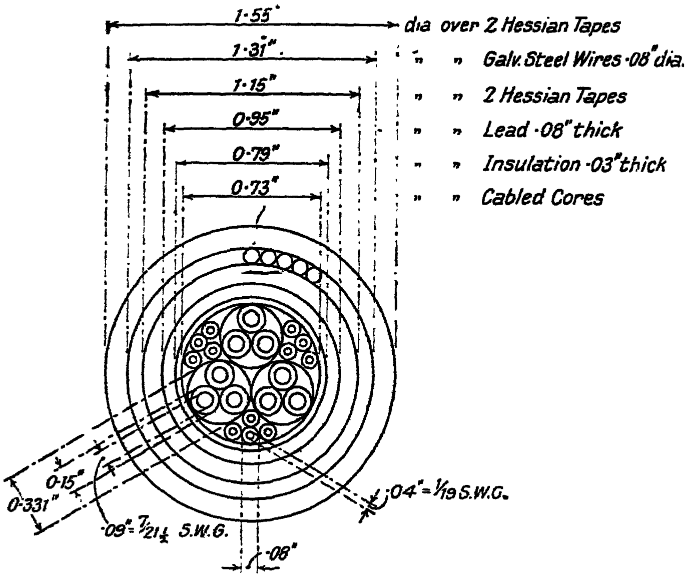


FIG. 37. PLAIN MULTICORE PILOT CABLE WITH TELEPHONE PAIRS

have proved satisfactory in service. A plain three-core pilot cable complies with the following specification—

Size of cores	7/·029
Resistance per mile	9·29 ohms
Capacity one core against remaining cores and lead	0·27 microfarads per mile
Capacity core to core . . .	0·165 microfarads per mile
A.C. pressure test for 15 min. at works	2500 volts
A.C. pressure test for 15 min. on site .	1000 volts

In a multicore cable each set of pilot wires per protective system should be separately grouped and

wormed, or screened in order to be unaffected by external influences.

It is sometimes erroneously thought that the need for well-insulated pilot wires is due to the voltage applied to them by the transformers of a voltage-balance Merz-Price system. This voltage, however, under the worst conditions is only a few hundred volts, whereas in service the pilot cable is subjected to very much higher voltages from external influences by the power mains.

Fig. 38 illustrates an interesting example of how a pilot cable is carried by a catenary construction on the main transmission line poles. Particulars of this transmission line and the protective system employed are given on page 944.

The Merz-Price Class

Type "A" Merz-Price Systems

Systems of this type possess the advantage of constant fault and relay settings, as shown in the stability diagram Fig. 29, already described on page 929. Modern systems employ various compensations to neutralize the normal-frequency out-of-balance currents and keep their encroachment small so that good stability is obtained with reasonably low fault settings. All the systems described below operate the switches at both ends of the main when any fault occurs within the protected zone.

Sheathed Pilot System. This system requires a special pilot cable, as shown in Fig. 36, having a sheath* surrounding each pilot wire which shunts the pilot capacity currents from the relays, as shown by the dotted arrows and condenser in Fig. 39. The pilot cable costs about 35 per cent to 40 per cent more than the plain pilot shown in Fig. 35. For pilot cables

* J. R. Beard and P. V. Hunter.

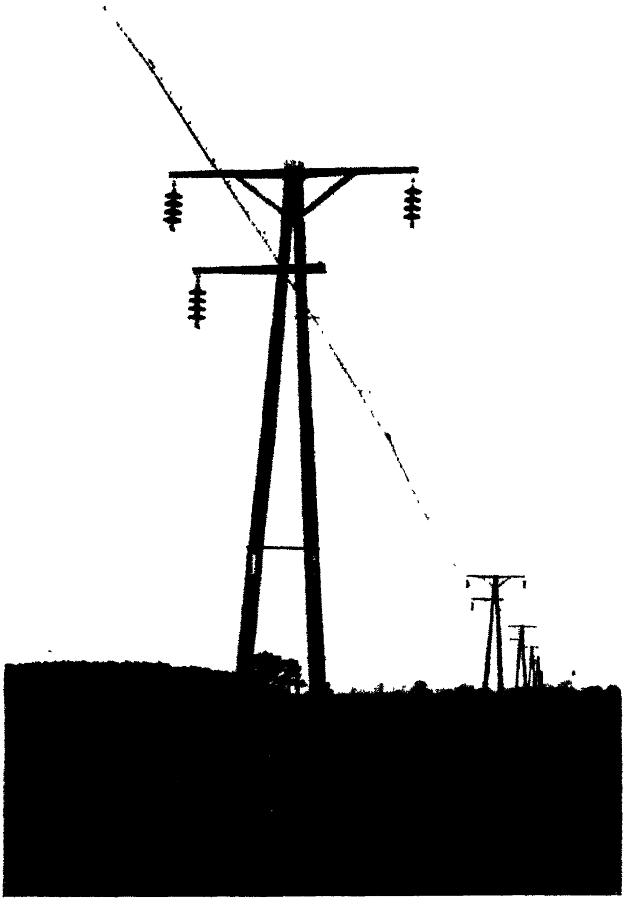


FIG. 38. 66 kV TRANSMISSION LINE PROTECTED BY MOCK PILOT PROTECTIVE SYSTEM
Showing Pilot Cable

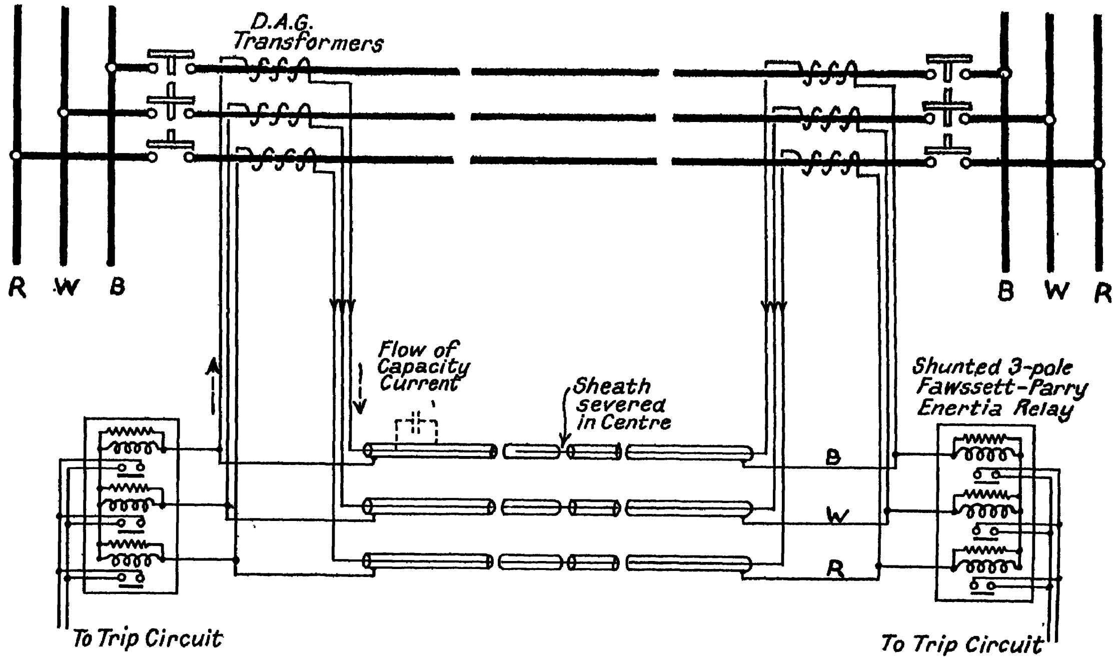


FIG. 39. SHEATHED PILOT PROTECTIVE SYSTEM

without telephone pairs the cost of a three-core sheathed pilot is approximately twice the cost of a plain three-core pilot. The sheaths of the pilot cable are apt to fracture if subjected to much mechanical strain, and for this reason this type of cable is not very suitable for locations where ground subsidence is to be expected or for use as shown in Fig. 38.

The system functions on the voltage-balance principle and transformer out-of-balance is reduced to a

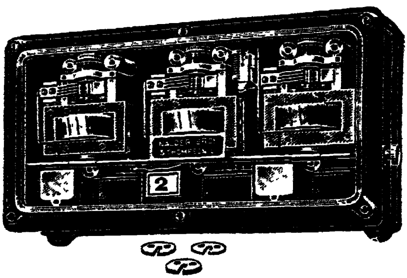


FIG. 40. REYROLLE-NALDER INERTIA TYPE FAWSSETT-PARRY RELAY

minimum by the use of D.A.G. type transformers. Fig. 40 shows the sensitive Fawssett-Parry type relay* employed having a setting of 30 to 80 mA and a volt-ampere consumption of 0·020. It is fitted with an inertia device† to stabilize it against mechanical shocks and electrical transients. Oscillatory stability is obtained by shunting the relay coils with non-inductive resistances, which increase the fault setting with the frequency in the manner shown in Fig. 32.

Mock Pilot System. This system, shown in Fig. 41, uses ordinary pilot cable and derives the title given to it by the Reyrolle Company from the method of pilot

* E. Fawssett and H. Parry.
† F. H. Nalder and B. H. Leeson.

capacity compensation employed. This consists in providing the relays with two windings acting in opposition. The capacity current from the real pilot circuit flows through one winding tending to operate the relay, and an approximately equal capacity current from the mock pilot circuit flows through the other winding tending to restrain the relay from operating.*

The system employs D.A.G. transformers and relays as shown in Fig. 40, but with duplicate and magnetically opposed operating coils. With the exception of the pilot capacity feature, it functions similarly to the sheathed pilot system, but requires higher fault settings to cover the out-of-balance due to lack of equality and phase difference between the concentrated capacity current of the mock pilot circuit and the distributed capacity current of the real pilot circuit. Fig. 38 shows a portion of the earliest 66,000 volts interconnecting network in Great Britain, comprising overhead lines and some underground cable. These are protected by mock pilot protective systems, and have been working satisfactorily on the North-east Coast for over two years.

An example of the switchgear associated with these protective systems is illustrated in Figs. 11 and 12 of Section IX, " Sitchgear."

Self-compensating System. This system, introduced by the British Thomson-Houston Company, is shown in Fig. 42, and derives its title from the special method employed for compensating the pilot capacity currents.†

The secondaries of the three solid-core current transformers at *A* and *B* are connected to the primary windings of conversion transformers, so that both earth and phase faults produce an appropriate current in the windings connected to the pilots.

* J. Whitcher.

† S. M. Lejeune and H. S. Petch.

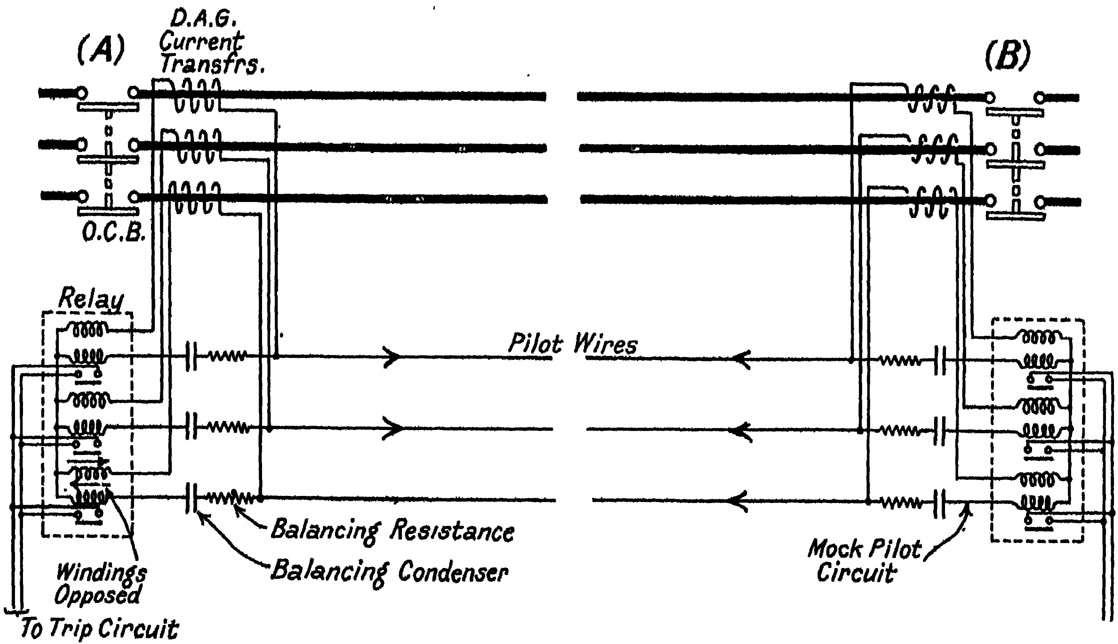


Fig. 41. Mock Pilot Protective System

The system functions on the current-balance principle, the relays and neutral pilot 2 being connected across the nominally equipotential points X and Y. Without the compensating transformer at A, pilot capacity current proportional to straight-through current would flow through the relays, as indicated by the dotted arrows and condenser. The function of the compensating transformer is to make what may be described as a phantom connection between the mid-points N of the transformer windings, and the neutral pilots, so that except under fault conditions, when it is required to operate, the potential along its length is midway between that of pilots 3 and 1, and no capacity current will flow. This is accomplished by inserting in the neutral pilot at each end the secondary windings of the compensating transformers, each of which produces a boosting voltage proportional to the voltage across the pilots 3 and 1, so that the potential of the neutral pilot at each of the points N' is substantially equal to that at the corresponding point N. The primary of the compensating transformer is energized, in proportion to the straight-through current, by the voltage drop across resistances in series with pilots 3 and 1. These resistances are adjustable for meeting various conditions of service, such as different lengths of main.

In the system shown in Fig. 42, stability is obtained by a constant fault setting based upon the maximum setting encroachment in accordance with Fig. 29. Alternatively, it may be secured by the addition of a biasing transformer, in which case the variable fault setting is determined by the Type "D" stability diagram (Fig. 58). Oscillatory stability is obtained by a vibrating reed relay as described later under the heading of "Biasing Transformer Protective System."

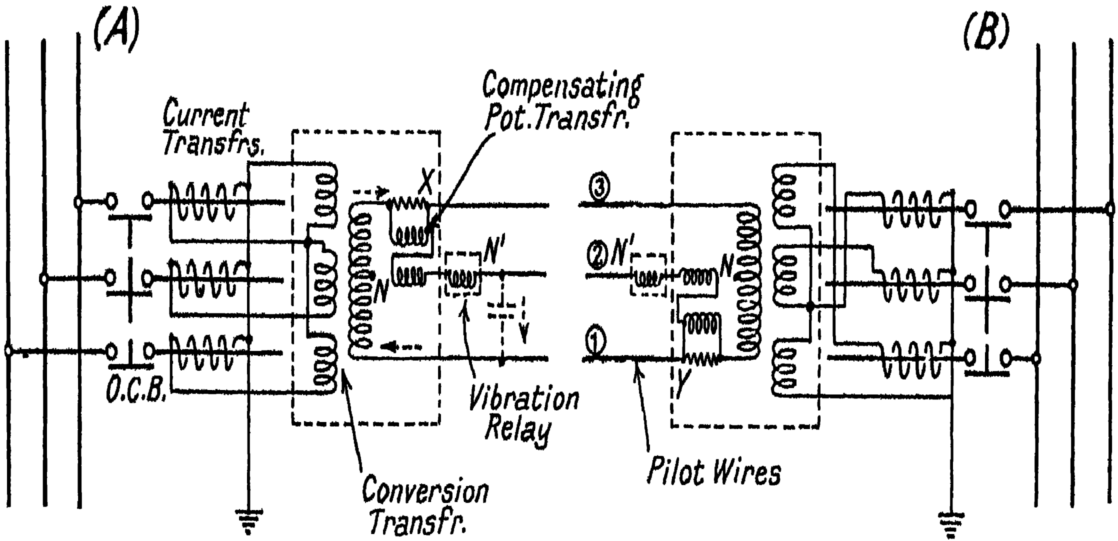


FIG. 42. SELF-COMPENSATING PROTECTIVE SYSTEM

Split Pilot System. This system, introduced by the Reyrolle Company, can function on either voltage or current balance, and derives its title from the use of two of the three pilot wires on the split conductor principle, by which pilot capacity currents are inherently self-neutralizing and operation occurs under fault conditions by disturbing the balance in the two split pilots.* The system shown in Fig. 43 functions on the current-balance principle and employs a mid-point tripping or operating connection, in the middle of the pilot cable, for disturbing the balance in the split pilots.† Transformer out-of-balance is reduced to a minimum by the use of D.A.G. transformers. The secondary windings of these transformers, as shown in Fig. 44, each have a different number of turns in the proportions indicated and are connected up in what is termed discriminating delta,‡ which enables discrimination for earth and phase faults to be obtained. In addition to its simplicity, this method has the advantage of subjecting the pilots to a minimum resultant voltage for a given straight-through current. Imagining the tripping connection to be removed, it will be clear from Fig. 43 that any current, capacity or other, flowing into the split pilots will divide equally between them and produce no flux in the split pilot transformers to operate the relays. The system without the tripping connection is thus inherently self-balancing and requires the addition of some means for producing operation.

When the main is healthy and carrying any value of current, X and Y are equipotential points, and therefore connecting them together by the tripping connection leaves the inherent balance of the system undisturbed.

When a fault, fed from A, occurs at F, the relays

* B. H. Leeson and E. W. M. Scott.
† H. Leben. ‡ *Ibid.*

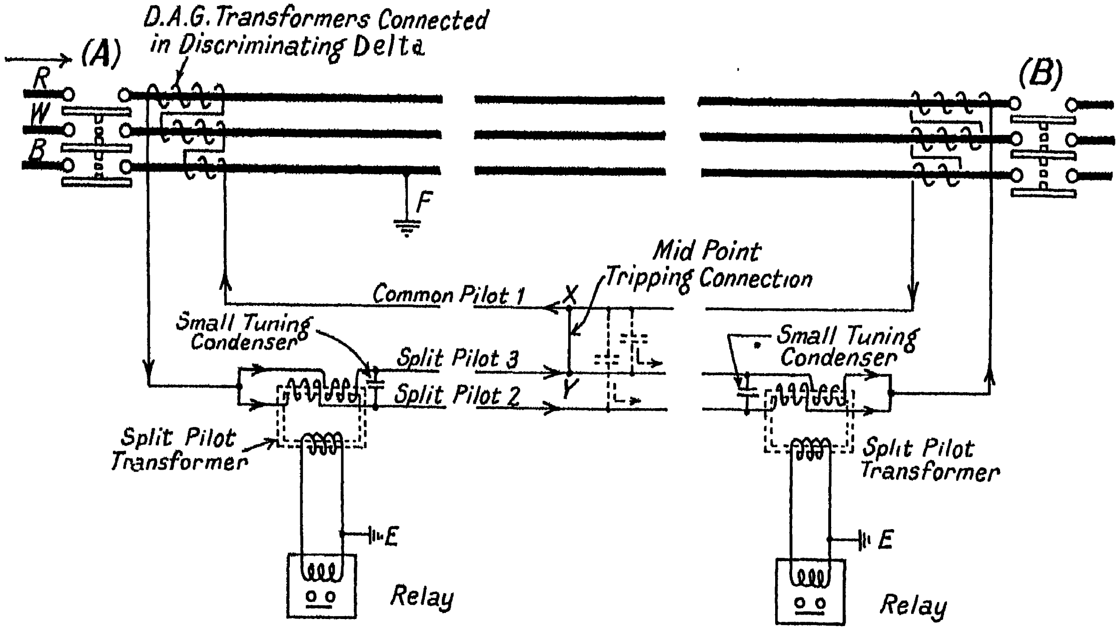


FIG. 43. SPLIT PILOT PROTECTIVE SYSTEM

at both A and B are operated. Neglecting the path shown dotted in Fig. 45, the out-of-balance current divides in the two split pilots in the directions indicated in a proportion of three to one. This produces a tripping effect at A proportional to three minus one, i.e. two, and a similar tripping effect at B proportional to one plus one, i.e. two. Although the shunting effect of the dotted path slightly alters the proportionality of the currents just described, the general principle that the difference between the two split pilot currents at one end of the main is equal to the sum of the split pilot currents at

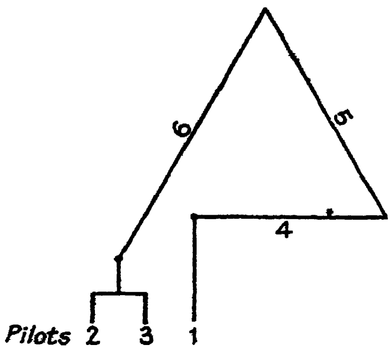


FIG. 44. PRINCIPLE OF DISCRIMINATING DELTA-CONNECTED TRANSFORMERS

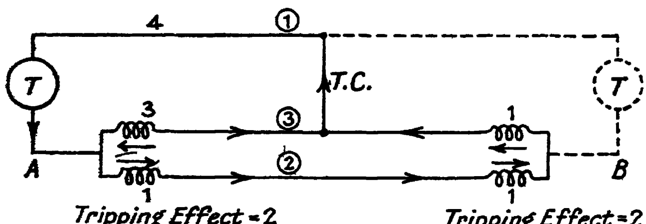


FIG. 45. TRIPPING CURRENT DIAGRAM

the other end is always true for any fault fed one way. For a fault fed both ways the tripping effect is intensified, but is still equal at both A and B.

The relays employed are of the single-pole Fawssett-Parry inertia type similar to that shown in Fig. 40.

and oscillatory stability is secured by electrical tuning of the split pilot transformers as described in connection with Figs. 32 and 34. Owing to the mutual inductance between the two split windings on the split pilot transformer, only a very small condenser is required to tune it electrically to normal frequency. Only a small voltage can occur across the condensers when the protective system operates; at other times the voltage is negligible. The relay circuits are earthed at both ends for safety.

Type "B" Merz-Price Systems

The principal feature of this type is the application of a restraining force proportional to the straight-through current, which tends to bias or prevent the relay from operating.* This causes both the relay and fault settings to be variable or biased, as shown in stability diagram (Fig. 46). Unlike Type "A," the stability factor is not necessarily a minimum at the rated straight-through current, although usually it is so.

The advantage of the variable fault setting is that it allows certain out-of-balance currents to be tolerated without increasing the rated fault setting, and an example of this is the use of solid-core transformers.

When a fault is fed from one end only, most protective systems of this type merely operate the switch through which fault current is fed, leaving the other switch closed. In many cases this does not matter, but in others it is a disadvantage. For example, consider two interconnected generating stations, one of which is used to earth the neutral of the network. When an earth fault occurs on the interconnecting main, the earthed generating station and a section of the network will be isolated from the fault, but the other station and the remainder of the network will be left as an

* E. B. Wedmore.

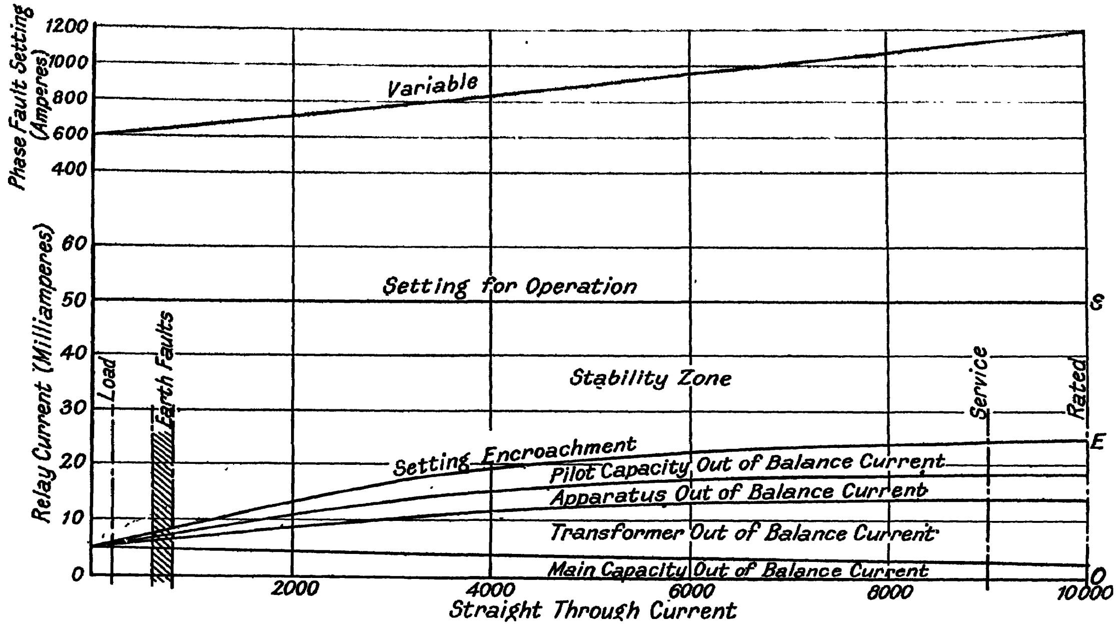


FIG. 46. NORMAL FREQUENCY STABILITY DIAGRAM FOR TYPE "B" MERZ-PRICE PROTECTIVE SYSTEMS
(Variable Fault and Biased Relay Settings)

insulated system with one phase earthed, and, in consequence, its insulation will be subjected to increased dielectric stresses.

Beam Relay System. This system,* manufactured by the General Electric Company, is shown in Fig. 47 and employs a mechanically biased relay with its operating coil connected directly to the secondary of its solid-core current transformer and its restraining coil in series with the pilot circuit.

The beam relay (Fig. 48) is biased by having its fulcrum slightly nearer the operating coil, and in consequence has the characteristic shown in Fig. 49. At light loads the curve rises because of the mechanical restraint incorporated in the relay, this being necessary for stability with respect to main capacity current. Ordinary pilot cables are employed and their capacity currents restrain the relay instead of tending to operate it. The system circulates about 0·25 amp. through the pilots at full load, and balance is obtained by a duplicate circuit, which for a three-phase system has a resistance equal to

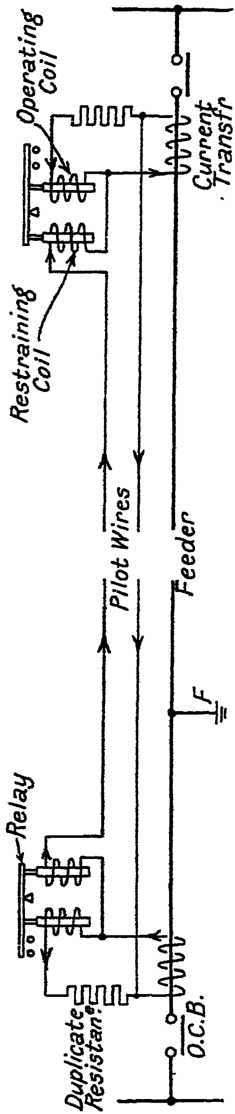


Fig. 47. The Beam Relay Protective System

* A. E. McColl.

one-half of that of a single pilot wire, in series with the operating coil. When the main is healthy, substantially equal currents flow round both the restraining and the operating coil of the beam relay. When a fault, fed from A, occurs at F, an increased current flows through the operating coil of the relay at A and causes operation. The switches at both ends

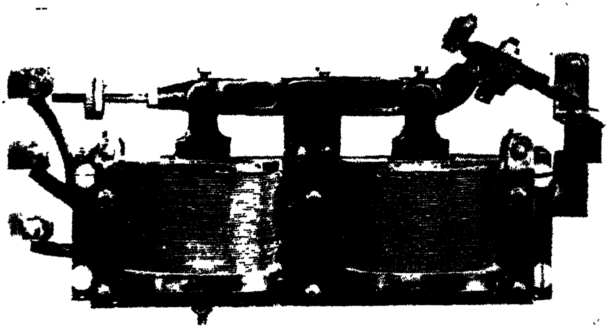


FIG. 48. G.E.C. BEAM RELAY

of the main are only operated when fault current is fed through each of them.

Tee'd Protective System. This system was developed by the Reyrolle Company to meet the demand for a protective system suitable for a tee'd main, from which it derives its title. The salient feature is the use of wattmetrical relays which are inoperative to leading pilot capacity currents in advance of the pilot voltage by approximately 90° and operative to out-of-balance fault currents approximately in phase with the pilot voltage.*

The system shown in Fig. 50 employs D.A.G. type transformers with different ratios, and each group is connected up in reverse delta so that it generates an

* E. B. Wedmore.

appropriate single-phase voltage for phase and earth faults. The transformer groups are connected up to the relays and to a plain two-core pilot cable on the voltage-balance principle.

The protective relay shown in Fig. 51 is constructed on similar lines to those described in connection with Fig. 20, and is provided with a wattmetrical feature

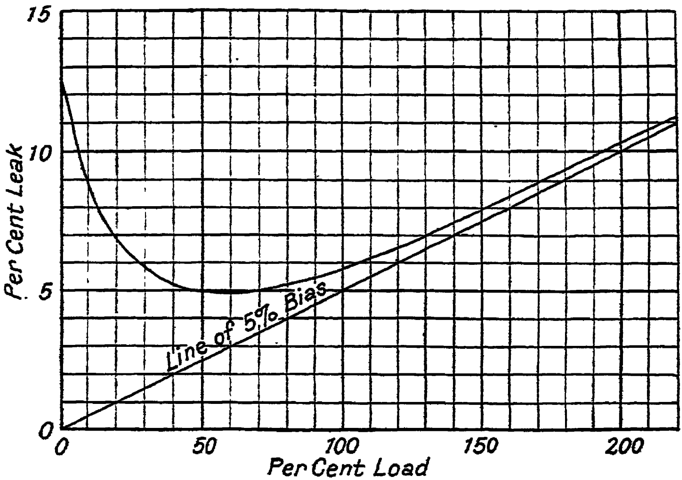


FIG. 49. CHARACTERISTIC CURVES OF G.E.C. BEAM RELAY

by having its current coil connected in series with the pilot wire and its voltage coil across the pilot wires. The stability and operation of the system thus depend upon the vector relationship between the current and voltage in the pilot circuit.

Normal frequency stability is obtained by the transformer out-of-balance being inherently small and the leading pilot capacity out-of-balance current having practically no operative effect on the relays. As the pilot wires have considerable resistance, and the

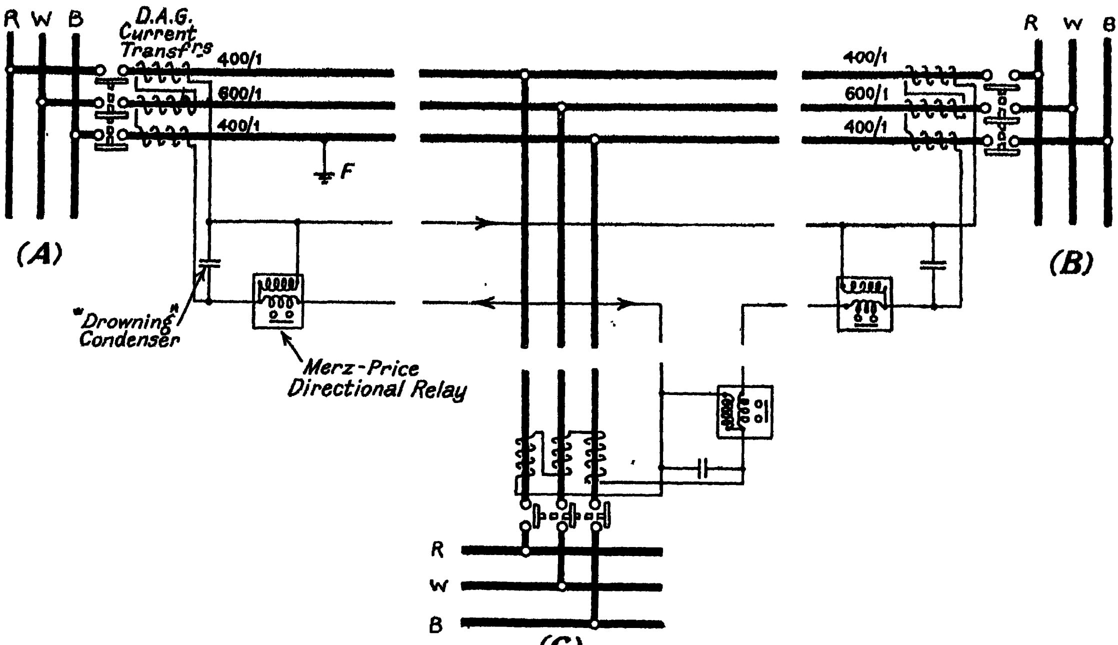


FIG. 50. TEE'D FEEDER PROTECTIVE SYSTEM

capacity is distributed along their length, the charging current in practice is less than 90 degrees in advance of the pilot voltage and the longer the pilot the more they tend to become into phase. The relays, therefore, are provided with power factor compensation and a

FIG. 51. DIRECTIONAL MERZ-PRICE RELAY

variable fault setting which increases with straight-through current.

The problem of obtaining oscillatory stability is not one of merely diverting the out-of-balance high-frequency currents from the relays, but is one of maintaining their correct phase relationship with the pilot voltage. For this reason oscillatory stability is obtained by connecting across each transformer group drowning condensers* which both divert high-frequency currents and preserve the required phase relationship.

* R. W. Biles and E. W. M. Scott.

With a fault at F fed from A and C only, an out-of-balance current approximately in phase with the pilot voltage is produced, and operates relays and switches A and C. Owing to the directional feature of the relays this system only operates switches through which fault current is fed.

Translay System. This system,* introduced by the Metropolitan-Vickers Company, is shown in Fig. 52 and derives its title from the combination of an auxiliary transformer and a wattmeter relay into one unit.

In general principle the system functions on voltage balance, similarly to the tee'd protective system just described, so that in effect its stability and operation depend upon the vector relationship between the current and voltage in the pilot circuit.

The main feature of the system is the special transformer-relay shown in Fig. 52 which permits the use of ordinary metering-type current transformers and two telephone pilot wires as far as the system itself is concerned. The core of the transformer-relay element has three primary windings on its centre limb, which are connected to the three current transformers in a manner analogous to the overcurrent and earth leakage system shown in Fig. 11. This causes the secondary winding S to generate a voltage of about 35 when full load current flows in the main, but owing to saturation the voltage is limited to about 130 R.M.S. volts for the highest fault current. The two transformer secondary windings S are connected on the voltage-balance principle in series with the windings of the relay operating elements and the pilots.

The translay relay shown in Figs. 52 and 53 has an induction disc movement which operates on the wattmeter principle with a small inverse time characteristic. The main and preponderating flux is produced by the

* T. W. Ross.

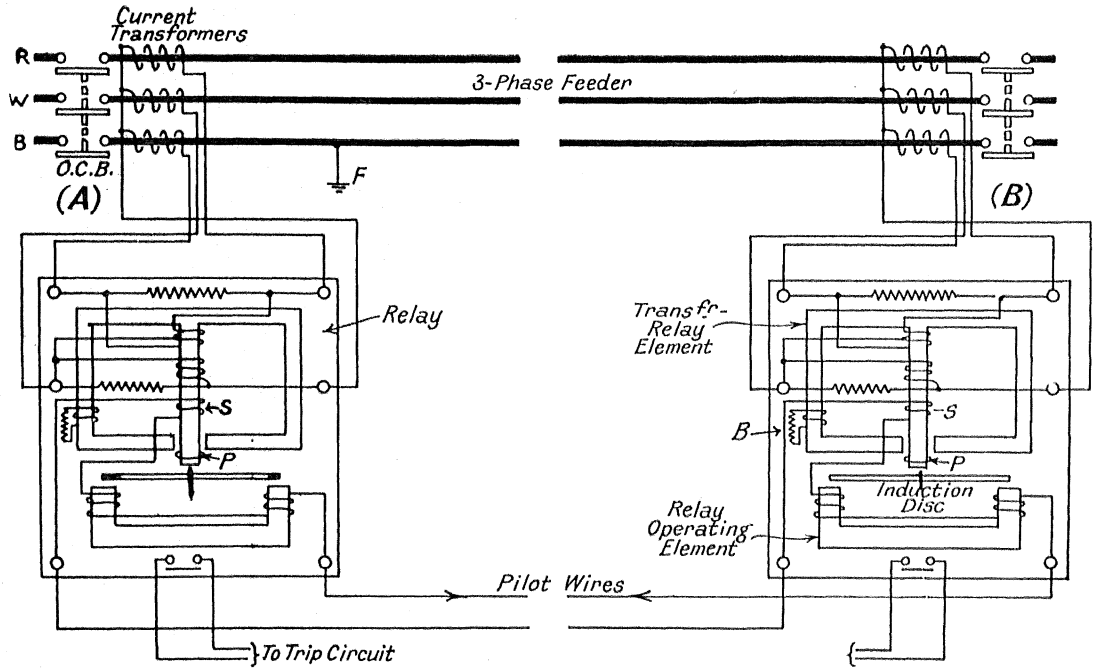


FIG. 52. TRANSLAY PROTECTIVE SYSTEM

upper transformer-relay element which forms a burden on the current transformers. It therefore requires a small current to flow in the relay operating element to cause an interaction of fluxes and the consequent operation of the induction movement of the relay.

With a fault at *F* fed from *A*, the increased voltage generated by the transformer-relay element at *A* causes

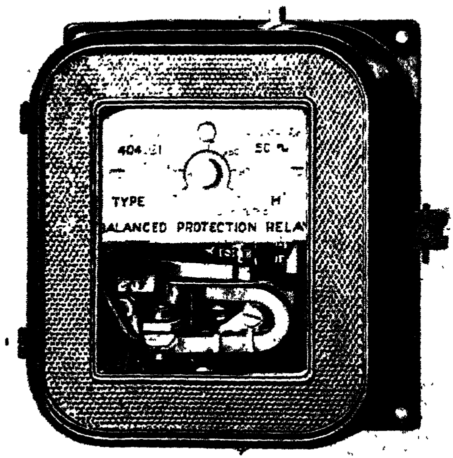


FIG. 53. METROPOLITAN-VICKERS TRANSLAY RELAY

a current to flow approximately in phase with the pilot voltage which operates relay and switch *A*. The switches at both ends of the main are only operated when fault current is fed through each of them.

Normal frequency stability for transformer out-of-balance is secured by a bias giving the relay a variable fault setting and is produced by the resistance-loaded coil *B*. The relay is inoperative to leading pilot capacity current in advance of the voltage by a nominal

90 degrees, depending upon the length of the pilot cable (as already described) and is adjustable for this by the compensating winding *P*.

Oscillatory stability is provided for by shunting the overcurrent and leakage windings with non-inductive resistances.

Type "C" Merz-Price Systems

The principal feature of this type is the use of a device which operates at a given straight-through current and causes a proportion of the out-of-balance currents to be diverted from the protective relay.* This causes the fault setting to be graded, although the relay setting remains constant, as in stability diagram Fig. 54. The stability factor is not necessarily a minimum at the rated straight-through current. The advantage of the graded setting is that it enables certain out-of-balance currents to be tolerated without increasing the rated fault setting.

Two-core Diverter Relay System. This system, introduced by the Reyrolle Company, is shown in Fig. 55 and provides low earth fault settings and between-phase protection with a plain two-core pilot cable.† This is accomplished by the combined use of solid-core balance transformers for earth faults‡ and D.A.G. transformers for phase faults, all of which are connected in series with the protective relays and pilots on the voltage-balance principle. Two special relays are employed as shown in Figs. 56 and 57.

The anti-surge relay§ (Fig. 56) has an electrical movement of the Fawssett-Parry type which can act instantaneously, but the contact-making member is governed by an inertia device which stabilizes the relay by a small time hesitation of about 0·1 sec. Under

* R. W. Biles. † B. H. Leeson and R. W. Biles.
‡ Ferranti-Hawkins. § B. H. Leeson.

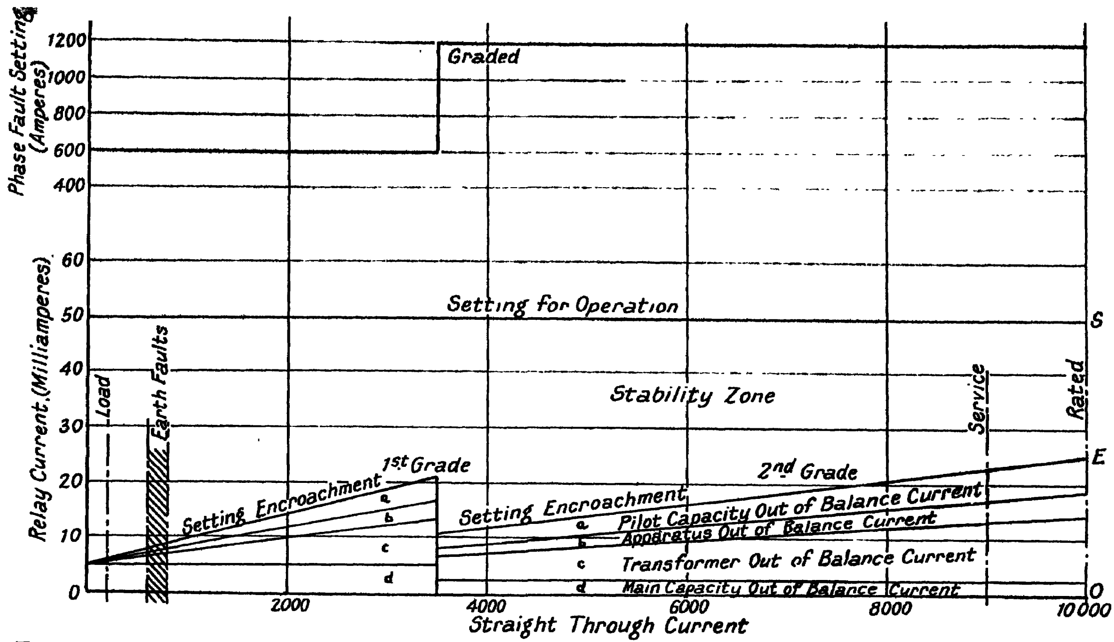


FIG. 54. NORMAL FREQUENCY STABILITY DIAGRAM FOR TYPE "C" MERZ-PRICE PROTECTIVE SYSTEMS
(Graded Fault and Constant Relay Settings)

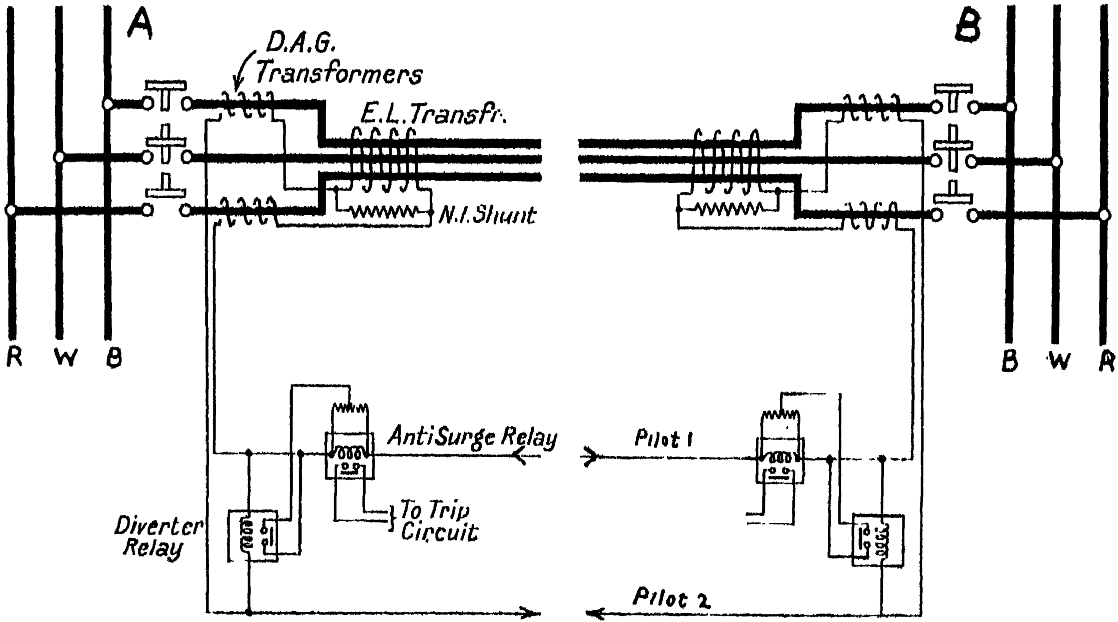


Fig. 55. Two-core Diverter Relay Protective System

fault conditions these relays operate the switches at both ends of the main, irrespective of whether the fault is fed one way or both ways.

The diverter relay* (Fig. 57) is a high-speed relay and operates in about 0·04 second when the voltage

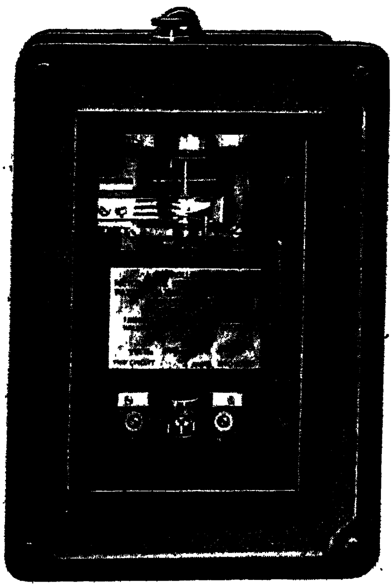


FIG. 56. REYROLLE ANTI-SURGE RELAY

across the pilots corresponds to the desired straight-through current.

When the diverter relays operate, they short-circuit resistances which shunt the anti-surge relays, so that the current tending to operate them is diverted, and the fault setting is increased.

The diverter relays are inoperative to limited earth

* R. W. Biles.

faults, but instantly grade the fault setting on a straight-through fault current. The grading ensures normal frequency stability for the out-of-balance currents caused by the solid-core earth leakage transformers and pilot capacity. Oscillatory stability is

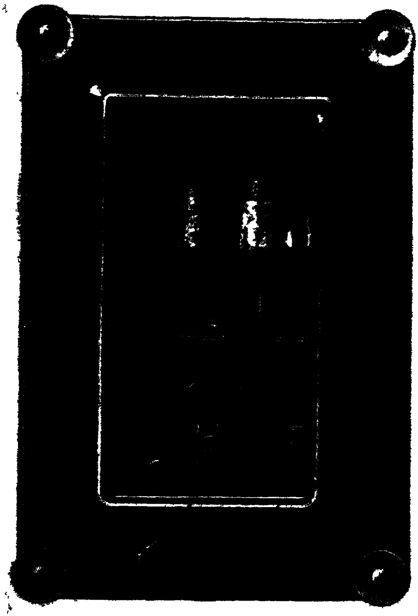


FIG. 57. REYROLLE DIVERTER RELAY

obtained by non-inductive resistances shunting both anti-surge relays and earth leakage transformers.

TYPE "D" MERZ-PRICE SYSTEMS

The principal feature of this type is the use of an auxiliary biasing or diverting device which causes a

variable amount of the out-of-balance current in the pilot circuit to be shunted from the protective relay in proportion to the straight-through current. This causes the fault setting to be variable, although the relay setting remains constant as shown in the stability diagram (Fig. 58). The stability factor is not necessarily a minimum at the rated straight-through current. The advantage of the variable fault setting is that it allows certain out-of-balance currents to be tolerated without increasing the rated fault setting.

Biasing Transformer System. This system, shown in Fig. 59, was introduced by the British Thomson-Houston Company and derives its title from the special transformers which are used to couple the relays to the pilot circuit and give them a biased or variable fault setting in respect to the current in the main.* The system functions on the voltage-balance principle over three plain pilot wires with no separate capacity compensation and employs double transformers of the solid-core type with a special method of connection* for utilizing separate phase and earth fault relays, the latter having lower fault settings.

The method of connection is similar to that of the overload and earth leakage systems shown in Fig. 11. The double transformers on the two outer phases function as one transformer and are in parallel with one transformer on the centre phase. The two transformer groups thus formed at each end of the main are connected in series by the neutral connections N, the phase fault relay primary windings, and the two outer pilot wires, in which single-phase current flows or is balanced. The third or centre pilot wire is connected to the two neutral points N in series with the earth fault primary windings. With this system switches at each end of the main are operated for a fault fed one or both ways.

* A. S. Fitzgerald

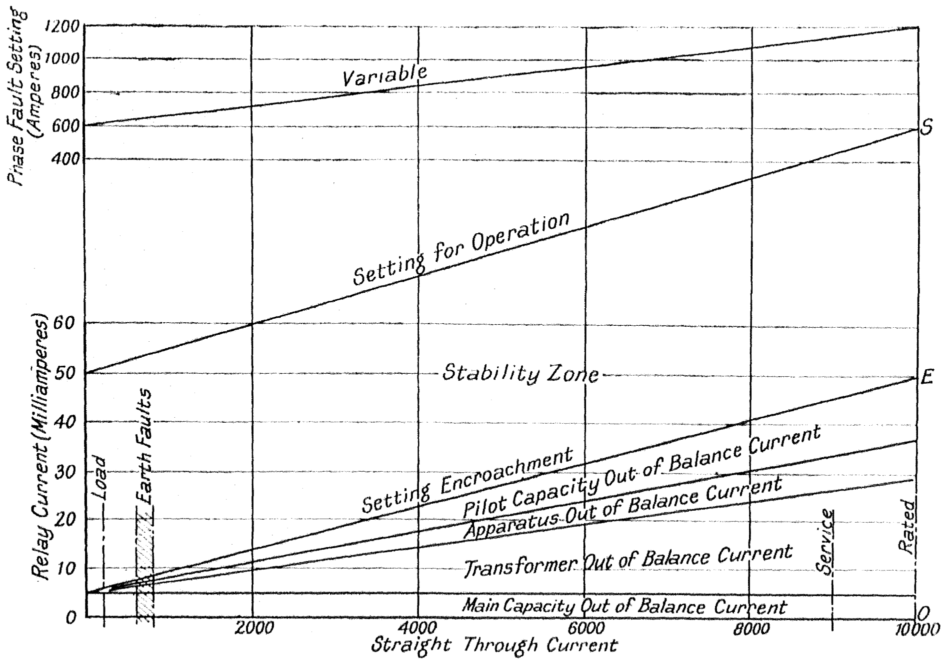


FIG. 58 NORMAL FREQUENCY STABILITY DIAGRAM FOR TYPE "D" MERZ-PRICE PROTECTIVE SYSTEMS
(Variable Fault and Constant Relay Settings)

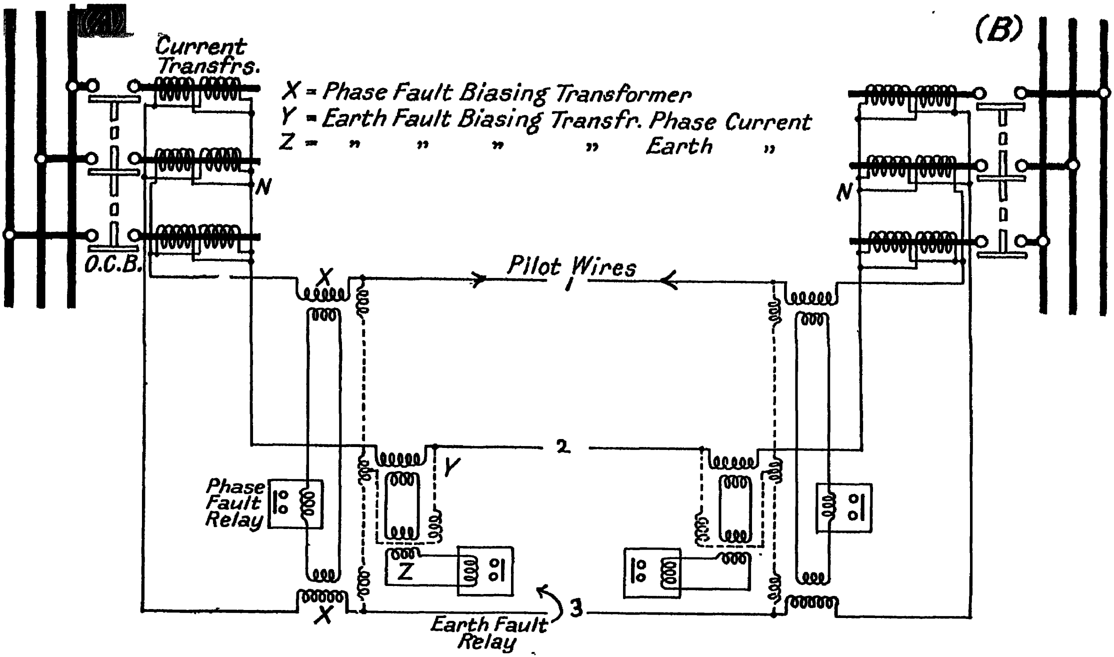


FIG. 59. BIASING TRANSFORMER PROTECTIVE SYSTEM

The biasing transformer (Fig. 60) has a three-limbed core and three separate windings. The relay primary winding is connected in the pilot circuit, and but for the restraining winding would generate current in the relay secondary winding like an ordinary transformer. The restraining windings are wound so that they are non-inductively linked with the other two windings,

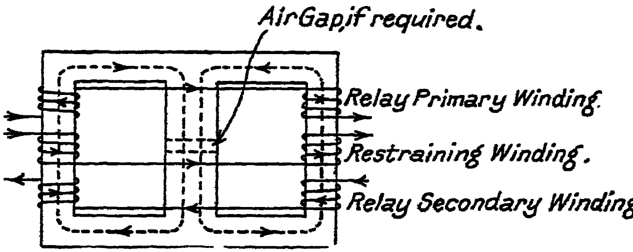


FIG. 60. PRINCIPLE OF BIASING TRANSFORMER

but produce fluxes as shown by the dotted arrows when carrying current roughly proportional to the current in the main. The core becomes saturated by these fluxes, and the ratio of transformation between the relay primary and secondary windings decreases because it becomes governed by the degree of saturation of the core instead of by the normal turns ratio of the windings.

As shown in Fig. 59, there are three biasing transformers, X, Y, and Z. The relay primary and secondary windings are shown horizontal with the restraining windings vertical. For phase fault bias the restraining windings are connected across the pilots, and for earth fault bias the restraining windings are connected in series with the centre or neutral pilot wire. If the current in the main increases, a larger current flows through the restraining windings of the biasing transformers, the ratio of transformation decreases, and the fault setting is increased as desired.

To obtain normal frequency stability, the biasing transformer is required to increase the fault setting in respect to both out-of-balance transformer and pilot capacity currents which, however, may have different phase relationships.

Oscillatory stability is obtained by the use of a mechanically tuned relay similar in principle to that shown in Fig. 33, but differing in the details of its construction* and in its contact-making device† from that shown in the illustration.

E.H.V. Split-pilot System. Another example of type "D" Merz-Price systems is the Reyrolle E.H.V. split-pilot protective system employing solid-core transformers and it is mentioned here for the purpose of completing the classification as shown in Fig. 58.

THE SPECIAL MAINS CLASS

As the above heading implies, protective systems in this class are only applicable to electric mains constructed in a special manner, and they have been evolved for the same reason as those in the feeder arrangement class, namely, to obtain discriminating protection without the use of pilot wires or time grading.

These protective systems usually have variable fault settings and junction upon the principle of either differential balance or insulation breakdown. They may, therefore, be classified into two generic groups.

The first is the split-conductor group of systems, in which the main is constructed with separate and parallel, or split, conductors, through which the load current divides equally. This is a development of parallel feeder protection, in which discrimination for stability and operation depends upon the balance or

* H. S. Petch and P. H. Harding.
† A. S. Fitzgerald.

out-of-balance between the currents flowing at the same end of two mains.* In certain systems in this group the split conductors function additionally as pilot wires carrying currents superimposed upon them on the voltage-balance principle.

Good systems of this type provide excellent protection and stability with low fault settings, and are extensively used. Their more universal use has been restricted either because the capital cost of the special main and equipment exceeds the cost of an alternative system of the Merz-Price class with its ordinary main and separate pilot cable, or because of the limitation imposed in constructing satisfactorily certain special cables for extra high voltages.

The second generic group is the sheath group, in which the conductors forming the main are surrounded by a sheath, through which no-load current passes under healthy conditions, but which under fault conditions carries a fault current for operating the protective relays. The sheaths can be normally at the same potential as the main conductor, earth, or be maintained at an intermediate potential by an auxiliary supply.

Many practical difficulties arise in applying this type to mains working at the higher voltages, and, in consequence, their use is not very general.

Split-conductor Group

Split-conductor System. This system† requires a special cable of the type illustrated in Figs. 61 or 62 the cost of each being respectively about 20 per cent and 25 per cent more than ordinary three-core cable. With the cables illustrated in this book the cost per unit length of a split conductor cable is about

* E. B. Wedmore.
† C. H. Merz and P. V. Hunter.

10 per cent higher than the combined cost of an equivalent ordinary cable and three-core pilot cable. To obtain an equal division of load current between the two split conductors in each phase, it is essential in the concentric type of construction, and it may be desirable in the six-core type, to transpose the two

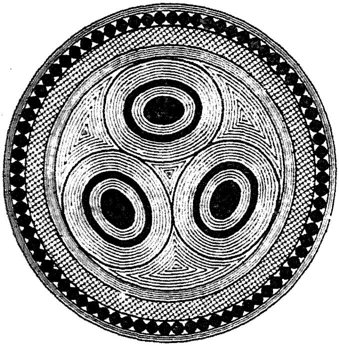


FIG. 61. 20,000 VOLTS, THREE-CORE SPLIT CONCENTRIC LEAD-SHEATHED, WIRE-ARMOURED CABLE

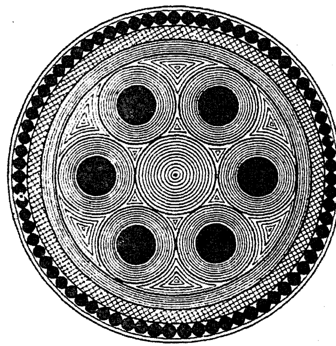


FIG. 62. 20,000 VOLTS, SIX-CORE LEAD-SHEATHED, WIRE-ARMOURED CABLE FOR SPLIT-CONDUCTOR SYSTEM

split conductors at certain cable joints along its length, so that each split conductor will have equal capacity and reactance values.

Reactance Transformer Type. The original system shown single-phase in Fig. 63 employs ordinary switches and reactance transformers. The primary windings on these are in series with the split conductors and are wound in opposite directions, so that when the main is healthy and equal currents flow through them in the same direction, no E.M.F.'s are generated in the secondary windings connected to the protective relays. Assume a fault at F fed from A ; at B the fault current flows from No. 1 split conductor through the reactance

transformer, and returns in the reverse direction to the fault F, thus operating the relay and switch B. At A the fault current divides unequally through the two splits because of the unequal reactances of the two paths, and this causes the relay and switch A to operate. The use of reactance transformers, however, has

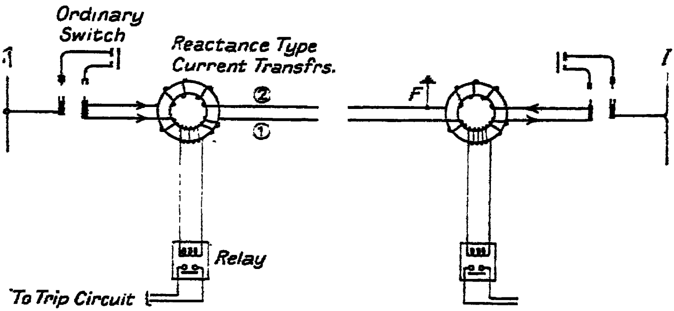


FIG. 63. REACTANCE TRANSFORMER TYPE OF SPLIT-CONDUCTOR PROTECTIVE SYSTEM

several disadvantages. The value of the reactance required depends upon the characteristics of the main, particularly its length, and this prevents standardization of equipment. On long mains the reactance transformers become cumbersome and expensive because of the large reactance value required and the large size of iron core needed to prevent saturation and keep the fault setting sufficiently high for stability.

Split Switch Type. In order to eliminate the reactance transformers and substitute simple and robust straight-through-type split conductor transformers, as shown in Fig. 64, the split switch illustrated in Fig. 65 was introduced. This parallels the split conductors before completing the circuit when closing, and vice versa when opening. This system has universal application and provides excellent stability with low fault settings.

With a fault at F, the relay and switch B operate by the fault current reversing, as already described. This disconnects the two split conductors at B and causes the fault current to be fed through split conductor 2, which in turn operates the relay and switch A. Expressed in other words, the split switch is a means

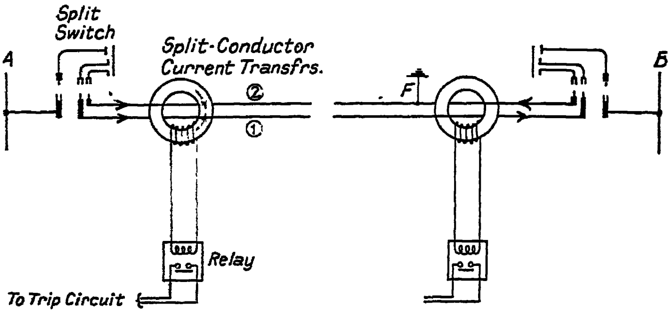


FIG. 64. SPLIT SWITCH TYPE OF SPLIT-CONDUCTOR PROTECTIVE SYSTEM

of introducing infinite impedance between the two split conductors at the time it is required.

The stability diagram (Fig. 66) indicates that the only out-of-balance current is that due to unequal impedance in the two split conductors. The fault setting is variable, being twice as high for a fault occurring in the middle of the main as for a fault adjacent to A or B. The system is very suitable for overhead transmission lines because it has the characteristic of operating immediately should one of the conductors break. In practice, certain restrictions in respect to guarding have been relaxed in view of this characteristic.

The system does not operate on a fault between split conductors, since, owing to the equality in potential along their length, no fault current will circulate between them.

Practical use over many years has proved that no disability is experienced from this characteristic. With good insulation there is little, if any, risk of a fault between split conductors, particularly in the six-core

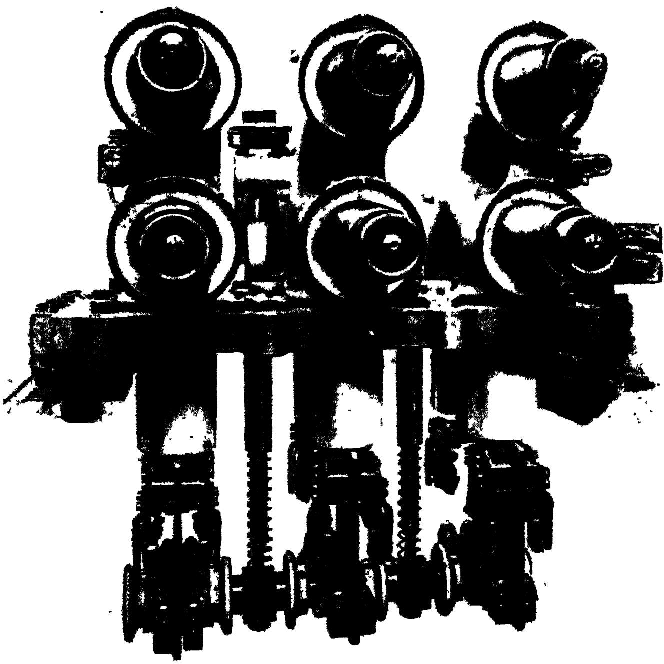


FIG. 65. REYROLLE SPLIT-CONDUCTOR CIRCUIT BREAKER

type of cable (Fig. 62), in which the split conductors are arranged diametrically opposite each other.

Reactor Type. This system,* which is used in Boston, U.S.A., operates with a fault between split conductors by giving them a potential difference along their length

* W. H. Cole.

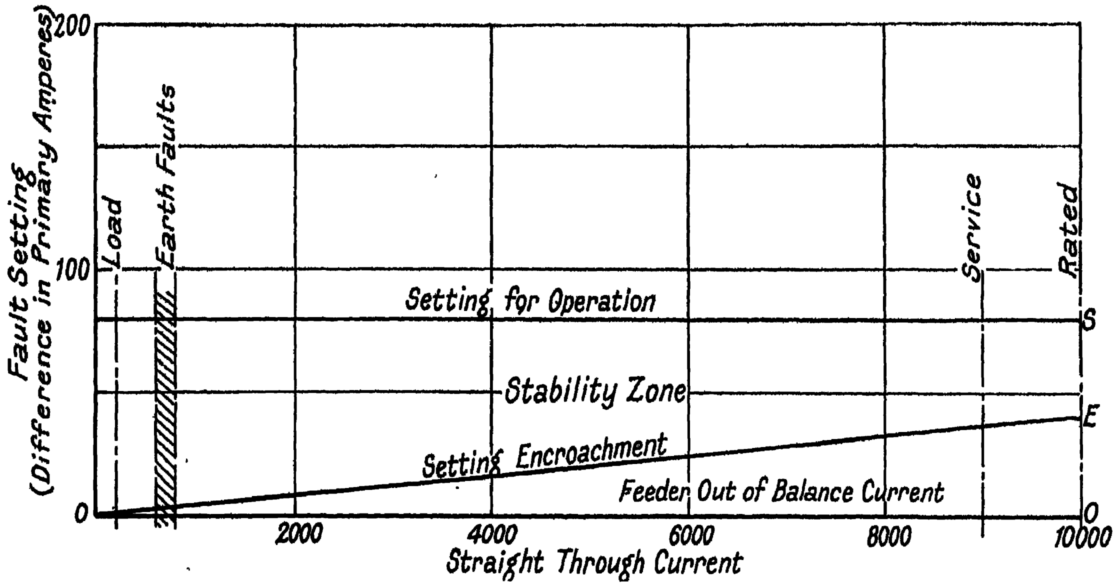


FIG. 66. STABILITY DIAGRAM FOR SPLIT SWITCH TYPE OF SPLIT-CONDUCTOR PROTECTIVE SYSTEM

while still retaining equal division of current. This is accomplished by inserting a suitable reactor in each split at opposite ends of the main and using an ordinary switch as shown in Fig. 67.

This system to discriminate correctly requires the concentric type cable, as shown in Fig. 61. The conductors are transposed in the middle of the cable, so that the reactors are connected to the outer split

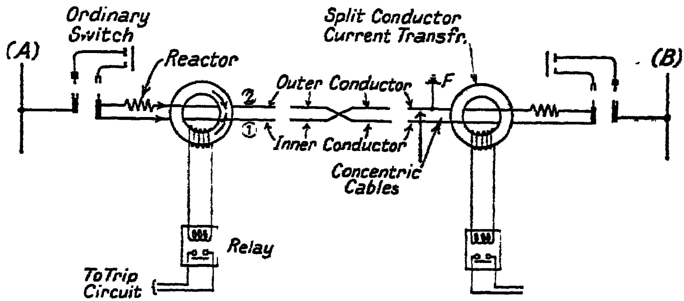


FIG. 67. REACTOR TYPE OF SPLIT CONDUCTOR PROTECTIVE SYSTEM

conductors, upon which all faults must occur. This ensures correct operation for a fault at *F* fed from *A* by providing two paths of unequal impedance through which the fault current divides in approximately the same way as in the reactance transformer type already described.

Unlike the reactance transformers shown in Fig. 63, which are self-balancing and non-inductive for load currents, the reactors in this system (Fig. 67) are inductive to load currents. They affect voltage regulation, and their characteristics must be balanced as accurately as possible. The fault settings should, therefore, be higher in this system than in the reactance transformer type because of the additional out-of-balance current introduced by the reactors. As the

reactors required for different mains vary, and there is a limit to their size and their cost, this system has a restricted field of application.

Lypro Protective System. This system,* introduced by the Dutch Lyn-Protectie Company, employs a cable

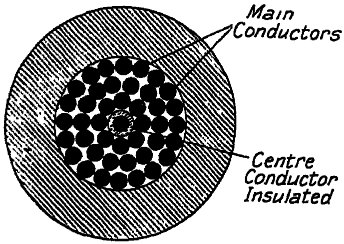


FIG. 68. SECTION THROUGH LYPRO CABLE

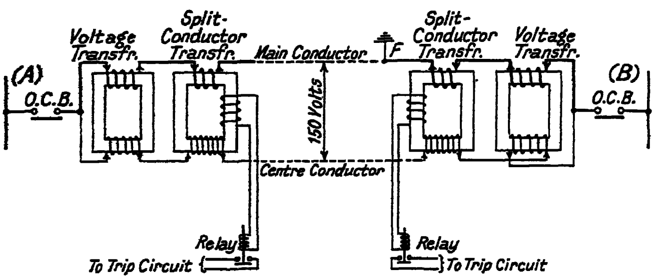


FIG. 69. LYPRO CABLE SYSTEM

as shown in Fig. 68, in which the centre strand, which carries a portion of the load current, is lightly insulated from the other strands, which form the main conductor.

Referring to the single-phase diagram (Fig. 69), the system operates on the reactance-type split conductor principle already described, the windings of the split conductor transformers being balanced on an ampere-turn basis. The centre and main conductors are connected to a voltage transformer at each end of the

* M. Höchstädter.

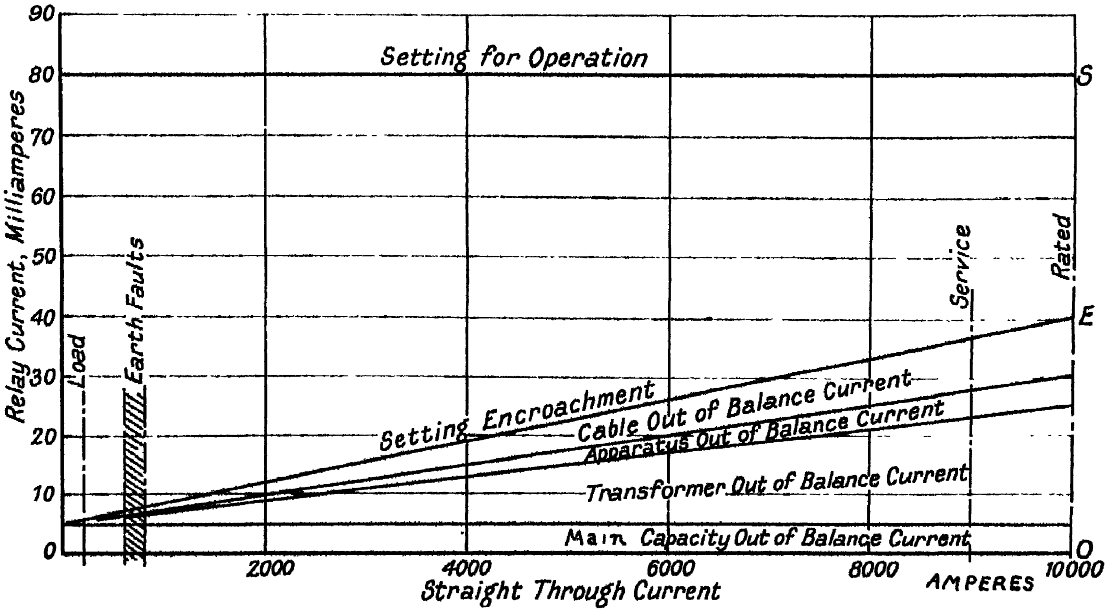


FIG. 70. NORMAL FREQUENCY STABILITY DIAGRAM FOR LYPRO AND PFANNKUCH PROTECTIVE SYSTEMS

main, which saturates at about 10 per cent load and produces an approximately constant voltage of 150 volts. The two voltages are superimposed on the centre and main conductors on the voltage-balance principle, and cause operation of the relays for a fault between the two conductors.

For a fault at *F* fed from *A*, the system operates similarly to the reactance transformer type split-conductor system, provided the insulation between the main and centre conductors does not break down. If the fault also short-circuits the main and centre conductors, operation of the relay and switch *A* is ensured by the current circulated by the voltage transformer.

The normal frequency stability diagram (Fig. 70) shows that the out-of-balance effects are a combination of those of the split conductor and Merz-Price voltage balance systems. Stability is obtained by making the constant relay setting sufficiently high. As in all split conductor systems, the fault settings are variable and depend upon the location of the fault. Oscillatory stability for the superimposed voltage-balance feature can be obtained by any of the means already described for systems employing pilot wires in the Merz-Price class. The chief merits of the system are the small extra capital cost of the cable, the mechanical protection afforded to the small centre conductor, and the use of ordinary switches.

Pfannkuch System. This system, introduced by the Allgemein Elektrizitäts Gesellschaft, employs a special cable, shown in Fig. 71, which costs about 5 per cent more than the standard type. The cable consists of a main inner core surrounded by an outer layer composed of alternately insulated and bare strands. There are three load-conducting paths, one consisting of the main inner core and the bare strands of the outer layer, and the other two containing each one-half of the

insulated strands of the outer layer connected in parallel. As shown in Fig. 72, each insulated group of the outer layer is connected to the main core in series with secondary windings wound in opposite directions on the protective transformers, and thus all the copper in the cable is utilized for carrying load current. The main core is in series with a winding on each protective transformer and produces a flux which divides equally

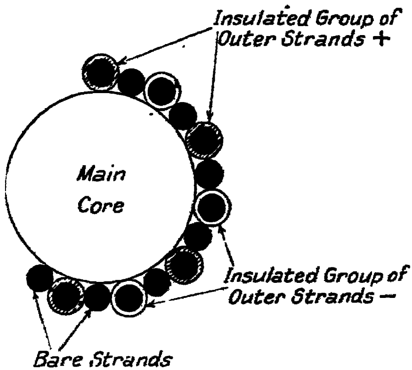


FIG. 71. PRINCIPLE OF PFANNKUCH CABLE

between limbs 2 and 3. This produces a voltage which is superimposed upon the two groups of insulated strands so that one group has a voltage of plus 50 to the main core and bare outer strands, and the other group has a voltage of minus 50.

The superimposed voltages are opposed on the Merz-Price voltage-balance principle and operate a sensitive relay to give a warning of impending breakdown in the cable, and a less sensitive relay for operating the switch. When the main is healthy and equal, fluxes pass down limbs 2 and 3 of the transformer as shown at A, no E.M.F. is produced in the relay windings because they are wound in opposite directions. If a

fault develops in the insulation of the main, a current flows in the secondary windings of limb 2. This causes a disturbance in the normal flux distribution, as shown by the arrows in transformer *B*, and current flows through the warning relay, the operation of which gives a visual or audible indication and connects the operating relay into circuit with an additional winding on limb 2. This alters the transformation ratio, and a current of approximately 60 per cent of the original value flows through the operating relay, which, if the fault is sufficiently severe, causes operation.

The winding on each limb 3, shunted by a condenser, compensates for capacity currents which flow in the insulated groups of outer strands caused by the superimposed voltage applied to them.

The normal frequency stability diagram is similar to Fig. 70 for the Lypro system. Both the relay and fault settings are constant, since the system operates in approximately the same way as the Merz-Price voltage-balance type. Oscillatory stability is provided for by non-inductive resistances, which shunt the transformer main windings as shown in Fig. 72.

Two of the merits of this system are its warning of a fault in its incipient stage, and its instantaneous operation when the fault develops into a short-circuit.

Another merit is that the two groups of insulated outer strands may be used for fault localization.

The system is most applicable to mains working at a voltage above 10,000 volts.

Sheath Group

Bowden-Thomson Protective System. This system, illustrated in Fig. 73, was introduced by the Macintosh Cable Company, and employs the special sheath cable shown in Fig. 74. The object is to make all insulation failures on the main conductors begin as earth faults

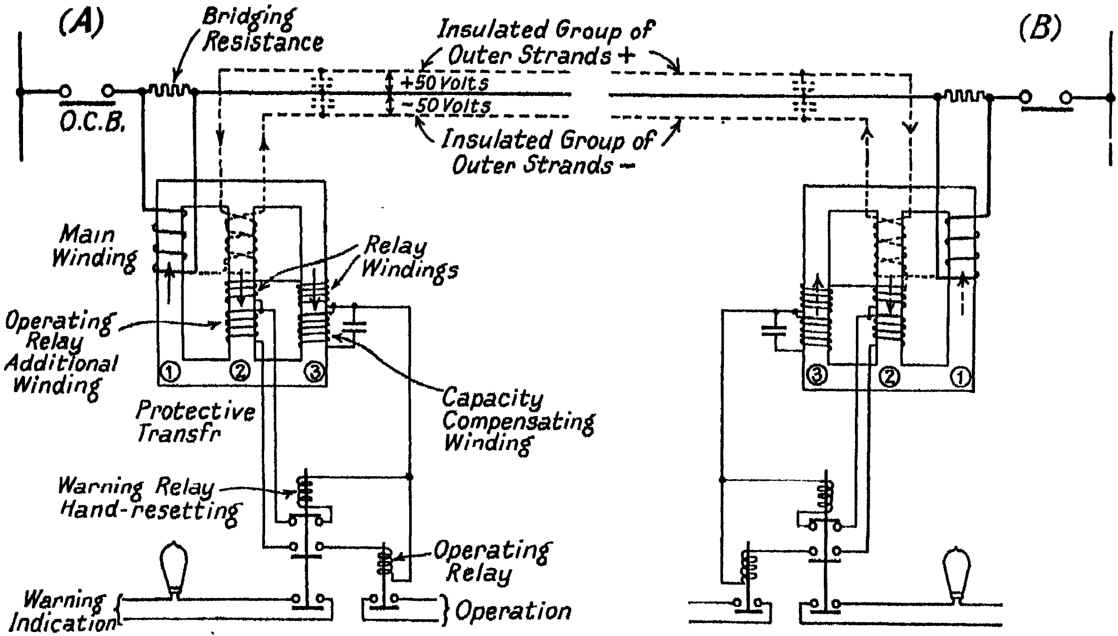


FIG. 72. PFANNKUCH PROTECTIVE SYSTEM

to the shields, through which the fault current flows to earth and operates the protective relays *D*. The metal shields *A* and *B* are connected to opposed secondary

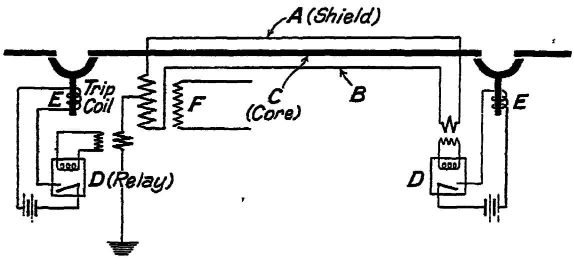


FIG. 73. BOWDEN-THOMSON PROTECTIVE SYSTEM

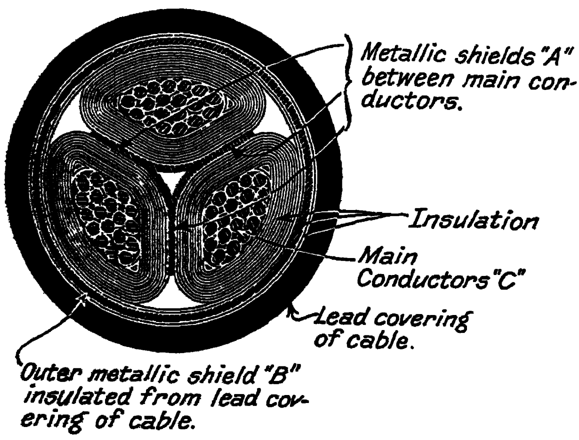


FIG. 74. SECTION OF BOWDEN-THOMSON SHEATHED CABLE

windings (earthed at a common point) of an auxiliary transformer which maintains each shield at an equal and constant potential to earth, so that, should either become faulty, the fault current flows to earth and operates the protective relays.

Other Protective Systems. Other examples of this type of protective system are the Callender-Waters system, in which all main conductors are surrounded by a common split sheath normally at earth potential, and the Whitaker system, in which each main conductor is surrounded by a sheath normally at the same potential as the main.

Rating. A typical rating for a protective system in this class is as follows—

Protective system	Split conductor
Switchgear	Split switches
Network	Three-phase resistor earthed neutral
Network voltage	11,000 volts
Network frequency	50 cycles
Length of main	5 miles
Type of main	Concentric, transposed joints
Normal load	200 amp.
Current transformer ratio	40/1–1
Straight-through current	10,000 amp.
Earth fault setting. All phases	Max. 160 amp. Min. 80 amp.
Phase fault setting. All phases	Max. 160 amp. Min. 80 amp.
Relay setting	·4 amp.
Time setting	Instantaneous
Stability factor	2
Tripping circuit	30 volts, 3 amp., direct current

If the fault settings are not given in detail the rated earth and phase fault settings are 160 amp.

THE DISTANCE CLASS

The choice of a suitable protective system for very long extra high voltage overhead transmission lines is governed by somewhat different considerations from those which apply to shorter and lower voltage lines or cables. For the latter, a protective system from the Merz-Price class usually offers not only the best

protection but also the most economical proposition for the reasons already explained.

The extra expenditure entailed in providing a pilot cable for the protection of an underground cable is represented by the cost of the pilot cable itself, because all charges for excavating, reinstatement, wayleaves, and other items are incurred irrespective of whether the pilot is provided or not.

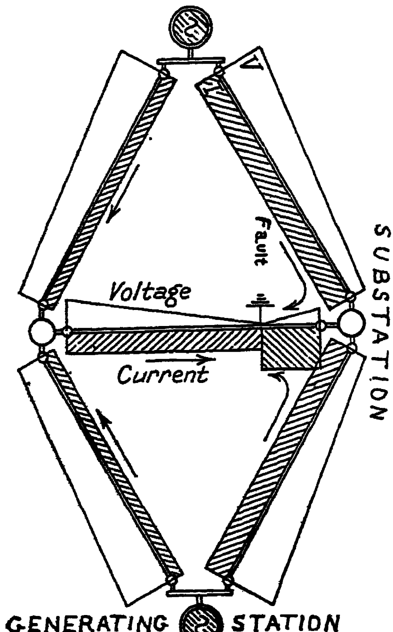


FIG. 75. VOLTAGE AND CURRENT CHARACTERISTICS OF FAULTY NETWORK

On overhead lines the pilot cable can, in certain cases, be laid along the route of a reasonably adjacent underground cable, but in other cases this cannot be done and the pilot cable has then to be buried separately or slung up on the poles of the main line by a catenary suspension wire, as shown in Fig. 38.

On very long extra high voltage overhead transmission lines the cost of a pilot cable, therefore, becomes an item for serious consideration whilst, at the same time, the alternative of selecting a protective system from the time-graded class is ruled out on account of the limitations inherent in this class.

This need has led to the comparatively recent development of what are called distance, positional, or impedance relay protective systems. The relays in these systems obtain their discrimination for operation or stability by automatically adjusting and grading their time settings in accordance with the conditions produced in the network by the fault itself. Although these protective systems fundamentally provide back-up protection, at the same time they go a long way towards solving the problem of providing unit protection without pilot cables.

General Principles. Distance or impedance relays function upon the distribution of current and voltage which exists in a network under fault conditions as illustrated in Fig. 75. In the diagram the fault current in each main is represented by the shaded characteristic and has its maximum value in the one which is faulty. The voltage is represented by the unshaded characteristics ; it will be seen that it has its minimum value at *F* and that it increases in value in proportion to its distance from the fault owing to the substantially uniform impedance of the mains.

If, at any given point, the voltage ordinate is divided by the corresponding current ordinate, the ratio represents not only an impedance value, but also a measure of the distance of the point from the fault. Thus, with a metallic short-circuit at the point *F*, the impedance value at the fault is zero, whilst the impedance values at the sub-stations nearest to the fault are lower than those at the most distant generating stations from which the fault is fed.

In order to obtain discrimination the relays nearest to a fault are required to operate first, whilst those farthest away must be prevented from doing so by a time interval for stability. From this it will be clear that if a relay can be designed to measure the impedance

value of the network at the point where it is installed and can be made to adjust its time setting accordingly, then it will provide a means for discrimination by time grading. Distance relays operate upon this principle by being given a maximum time setting which, however, automatically becomes faster as the voltage decreases and the current increases, that is, as the impedance value falls.

In principle, distance relays incorporate three fundamental elements. The first is a directional element which functions in a similar manner to that described for Fig. 20 and prevents the distance relay from operating unless the fault current flows from the busbar into the main. The second is an initiating element which functions upon under-voltage, overcurrent, earth leakage current, or a suitable combination of the three, and initiates the third element. This is the time-distance element which automatically grades the time setting of the relay in proportion to the current and voltage values, or impedance, in the manner already described. In certain relays two elements are made to perform the same function as these three fundamental elements.

In some relays the initiating element can be made to perform the function of distinguishing between earth and phase faults and of connecting the appropriate time-distance element in a manner best suited to correct operation by each particular fault.

For example, in a three-phase system three elements which operate on under-voltage may be made to perform the function of earth and phase fault selection (as just described) by utilizing the abnormal earth and phase voltage conditions which exist during the fault period.

Fig. 76 shows a portion of a ring main with four switching stations fed from two power stations A and D, and protected by distance relays numbered 1 to 8.

The fault F in the diagram is assumed to have no self-impedance, and hence the voltage characteristics rise from zero to the station voltages a' and d'. Equal fault currents flow through relays 2, 3, and 4 from A, and similarly through relays 5, 6, and 7 from D, but, owing to their directional elements, only relays 2, 4, 5, and 7 commence to function. Relays 4 and 5 operate first

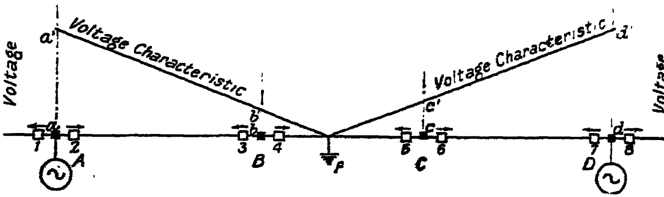


FIG. 76. PRINCIPLE OF DISTANCE PROTECTION

and isolate the faulty main in times proportional to the impedance values which, in this example, are proportional to the voltages represented respectively by $b\,b'$ and $c\,c'$. Relays 2 and 7, however, are prevented from operating by an interval of time for stability because their time settings are proportional to the larger impedance values represented respectively by $a\,a'$ and $d\,d'$.

Stability. Fig. 77 shows a typical stability diagram for the example represented in Fig. 76, and it illustrates how stability of relay 2 is secured when a fault F occurs anywhere on the adjacent main BC. The relay setting encroachment represents the time for a fault F to be isolated by relay 4 and its switch. It is required that the setting for operation of relay 2 shall provide a stability zone above this encroachment so that relay 2 of the healthy main shall be prevented from operating. As illustrated, the stability factor is a minimum at C, but this is not necessarily so and it may occur at any position along BC, depending upon the relative lengths

of the faulty and healthy mains and the shape of the relay characteristics.

For the fault shown at F—

$$\text{Stability factor} = \frac{\text{relay setting for operation}}{\text{relay setting encroachment}}$$

$$= \frac{OS}{OE} = 1{\cdot}5.$$

Application. Since the stability of a distance relay is dependent upon the difference in impedance values between the two ends of a main, and since the relay can only be made to respond to a certain minimum difference, it necessarily follows that there is a limit to the length of main which can be protected with a reasonable stability factor.

The minimum length of main is governed also by the relative lengths of the adjacent mains on either side of it, and this consideration is a very important one. Broadly speaking, distance relay protective systems are most advantageously used on transmission lines which exceed a length of about 12 miles.

It will be apparent that the method of discrimination, based upon the time-distance principle described above, is entirely different from that employed by the protective systems in the time-graded class. In the latter, the time grading is non-automatic, the time to isolate a faulty main increases towards the power station, and each relay requires a predetermined time setting. Further, a complete re-grading and an increase in time setting are required as extensions are made to the network. On the other hand, in distance relay protective systems, the time settings can have a uniform maximum value because they are automatically graded by the conditions produced by the fault itself. This enables a fault close to a power station to be cleared as expeditiously as a fault at any other point on the

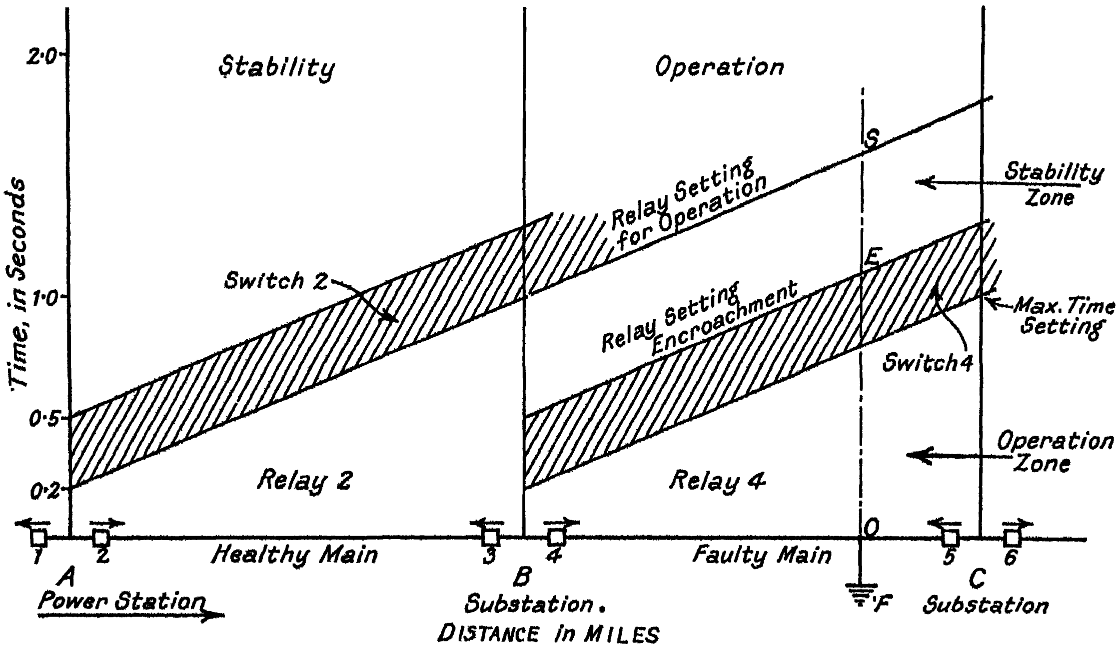


FIG. 77. STABILITY DIAGRAM OF DISTANCE PROTECTION

network and, except under special conditions, regrading is not required when the network is extended.

Metropolitan-Vickers Impedance Relay System. Fig. 78 illustrates the Metropolitan-Vickers Type "NZ"

FIG. 78. METROPOLITAN-VICKERS TYPE "NZ" IMPEDANCE RELAY

impedance relay which was originally developed in America. The time-discriminating element consists of two components, a current operating movement and a voltage restraining lever. The former, of the induction disc type, is made to rotate at a speed proportional to the driving force and in doing so winds up a spring which is fixed to the lever controlled by a voltage

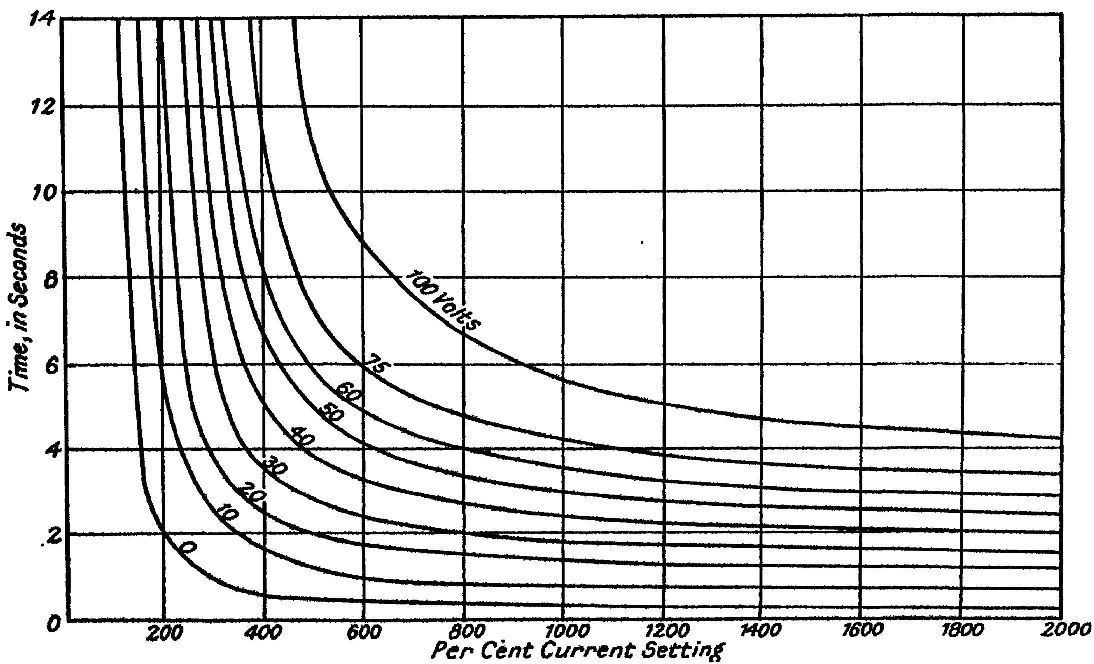


FIG. 79. CHARACTERISTIC CURVES OF METROPOLITAN-VICKERS IMPEDANCE RELAY

magnet. A contact-making member under the joint control of the current movement and voltage lever completes the trip circuit when the tension applied to the spring by the current operating movement overcomes the restraint due to the voltage magnet. Thus,

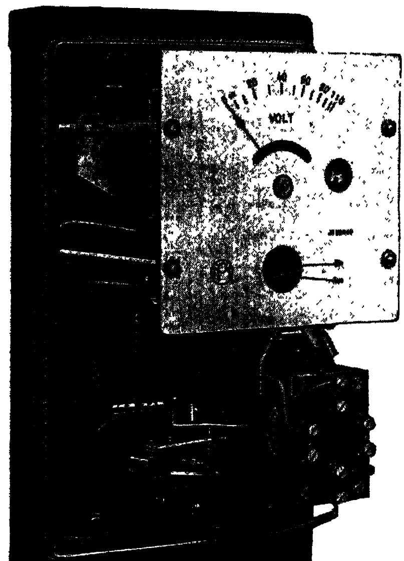


FIG. 80. PAUL MEYER IMPEDANCE RELAY

the time setting of the relay is a function of the voltage and current applied to it as shown graphically in Fig. 79, from which it will be seen that, for a given current, the time setting decreases with the voltage. A separate directional element is provided which ensures that the time-discriminating element is only operative when power flows from the busbars into the main.

Paul Meyer Impedance Relay System. Fig. 80 illustrates an impedance relay introduced by Dr. Paul

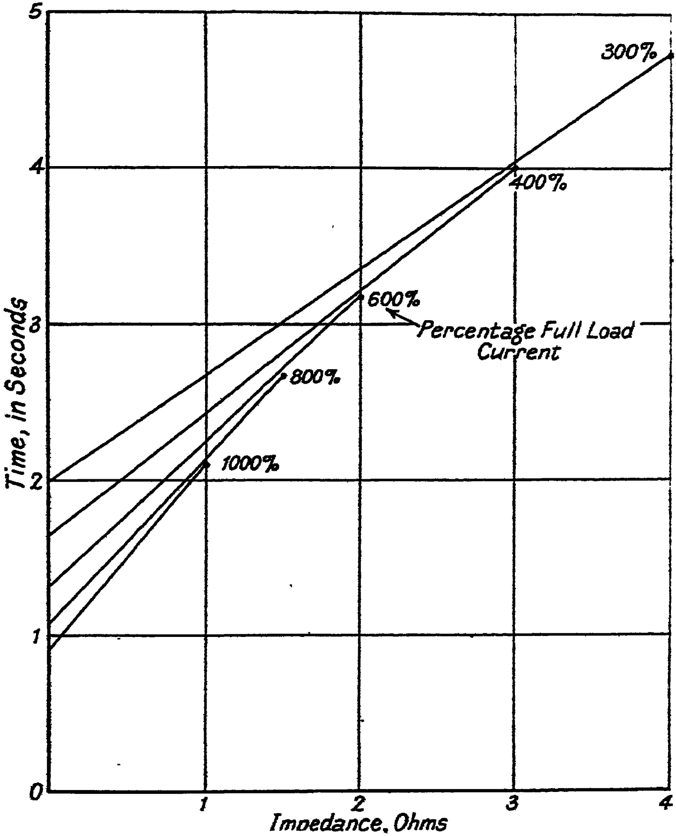


FIG. 81. CHARACTERISTIC CURVES OF PAUL MEYER IMPEDANCE RELAY

Meyer A.-G., Berlin, which was one of the first relays operating upon the distance principle. The chief difference between this relay and the one just described is

that a bi-metal strip is employed for timing purposes instead of an induction disc movement.

Fig. 81 shows the characteristic curves of this relay, and the principle upon which it works is illustrated in Fig. 82. The time-discriminating element consists

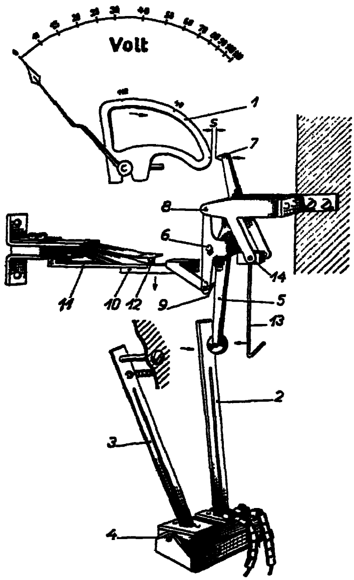


Fig. 82. Principle of Paul Meyer Impedance Relay

of a bi-metal strip (2), which is deflected to the right by the current, and a voltage movement which determines the position of the cam (1). A second bi-metal strip (3) is added for compensating for change in atmospheric temperature. The current causes the bi-metal strip (2) to press against lever (5) and move lever (7) towards the cam (1). When the lever (7) reaches the cam the whole mechanical system (5) pivots on (8) owing to the

point of contact between lever (7) and cam (1) becoming anchored, and finally causes the tripping contacts to close. Thus, the time setting is dependent upon the rate of deflection of the bi-metal strip due to the heating effect of the current and upon the position of the voltage-controlled cam which regulates the travel of the bi-metal strip. A separate directional element is provided which only permits operation when power flows from the busbars into the main.

Other Protective Systems. Other examples of protective systems in this class are the American General Electric Co.'s impedance relay, the Allgemein Elektrizitäts Gesellschaft impedance relay, the Brown-Boveri distance relay, and the Reyrolle ratio balance relay.

Rating. A typical rating of a distance relay protective system is given below.

Protective system	Impedance relay
Network	Three-phase, overhead, with multiple earthing
Network voltage	110,000 volts
Network frequency	50 cycles
Network reactance—	
(*a*) Between phases	·6 ohm per mile
(*b*) To earth	1 ohm per mile approx.
Network resistance—	
(*a*) Between phases	·5 ohm per mile
(*b*) To earth	·25 ohm per mile
Network voltage transformer	On L.T. side
Length of mains	25/50 miles
Normal load	200 amp.
Current transformer ratio	200/·5
Straight-through current	5000 amp.
Earth fault setting	200 amp.
Phase fault setting	400 amp.
Time setting, phase faults	1·1 sec. max. 0·25 sec. min.
Time setting, earth faults	1·0 sec. max. ·15 sec. min.
Switch operating time	0·3 sec.
Stability factor	1·3
Tripping circuit	110 volts, 3 amp., D.C.

The Author would like to thank the following for their permission to publish information, and for the help they have given—

Asea Electric, Ltd.
British Insulated Cables, Ltd.
British Thomson-Houston Co., Ltd.
Electrical Equipment & Carbon Co., Ltd.
General Electric Co., Ltd.
Metropolitan-Vickers Electrical Co., Ltd.
Nalder Bros. & Thompson, Ltd.
Newcastle-upon-Tyne Electric Supply Co., Ltd.
A. Reyrolle & Co., Ltd., and members of their staff.

INDEX TO VOLUME IV

INDEX

The items in this index are grouped together in sections
The numbers refer to pages

SECTION XIII

CARE AND OPERATION OF SWITCHGEAR

SECTION XIV
IRONCLAD SWITCHGEAR

SECTION XV
PROTECTIVE SYSTEMS FOR A.C. MAINS

END OF VOLUME IV

PRINTED IN GREAT BRITAIN AT THE PITMAN PRESS, BATH
B9—(5601)